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Central Aerohydrodynamic Institute (TsAGI)
Zhukovsky, Moscow region, Russia

"   " August, 1997

Final report

Experimental investigation of combustion stabilization in supersonic flow using free recirculation zones

Special contract (SPC-96-4043)
with Air Force Office of Scientific Research
(AFMC), USA, EOARD

Principal Investigator Vladimir Sabel'nikov

1997

Abstract

Final report summarizes shortly main results of three quarterly reports and presents experimental results on self-ignition and combustion stabilization in supersonic flow using free recirculation zone. Tests are conducted at hypersonic facility TsAGI T-131B. Measurements are performed in a nearly matched supersonic jet at the exit of two-dimensional channel over Mach number range M=2.0-2.8 at stagnation temperature range Tt=1200-1400K. Initial thickness of jet was equal 67 mm. Self-ignition and stabilization are obtained at T_t=1400K. Self-ignition was absent at T_t=1200K, 1300K. Thickness of free recirculation zone was about 25-30 mm.

Content

1. Introduction

Experimental investigation (e.g. [1-8]) shown, that interference of a concentrated vortex with shock wave at definite(critical) conditions results in breakup of vortex and shock wave and generation of a free recirculation zone and conical shock(generated by recirculation zone). It was also shown that geometry of free recirculation zone and flow parameters inside of free separation bubbles are nearly the same as for recirculation zones, which are generated at turbulent boundary layer - shock wave interaction.

Vortices in [1-3] were generated using different types of generators, e.g. semispan wing having a diamond shape airfoil section with was installed at the angle of attack to the incoming flow. This kind of generator allowed quite easily to vary vortex intensity by variation of angle of attack. Shock waves in [1-3] were generated by: 1) supersonic two-dimensional inlets, 2) blunt bodies, 3) wedges with different angles at edge, 4) simplest axysimetric diffusers (which were similar to supersonic nozzle).

In [5,6] phenomenon of free recirculation zone generation was studied at interference of vortex with a central shock wave (Mach stern) in overexpanded jets.

Already in [3] it was concluded that breakup of vortices and generation of free recirculation zones is determined mainly, by intensities of vortex and shock wave and does not depend on type of vortex and shock generators.

It is very attractive idea to use free recirculation zones for combustion stabilization in supersonic flow. High efficiency of such a kind of combustion stabilization in supersonic flow was demonstrated (with a forced ignition) in [9] at studding H_2- air combustion.

Free recirculation zone in [9] was generated at interference of shock waves with base wake behind of cylindrical model of diameter 20 mm in supersonic flow at M=2.1 and T_t =375K. It was found that at particular conditions, when base recirculation zone and free recirculation zone merge, the range of «rich» stabilization is considerably increased.

In [9] it was concluded, that generation mechanism of a free recirculation zone is the same as for separation zone at shock wave turbulent boundary layer interaction, when shock wave has a critical intensity. It was formulated that necessary condition of generation of a free recirculation zone is the equality of pressure rise in shock wave to stagnation pressure in the wake.

In [10,11] using numerical simulation self-ignition and stabilization was demonstrated in free recirculation zone (with lateral dimension about 5 sm.) of methane jet in supersonic flow with M=3 and T_t = 1400K.

The objective of present experimental investigation of liquid barbotaged kerosene in supersonic flow using free recirculation zone which is originated at interaction of vortex with normal shock wave. First two quarterly reports [12,13] presented experimental results of cold tests on generation of free recirculation zone. The influence of gas injection (fuel simulator) into vortex structure and vortex-shock wave interaction were studied. Third quarterly report [14] contained: 1) estimation of minimum dimension of free recirculation zone for combustion stabilization; 2) design and manufacturing of aerodynamic models (vortex generator, shock generator etc.) for tests in high enthalpy tests with combustion; 3) tests methodology was described.

Final report summarises shortly main results of three quarterly reports and experimental data on self-ignition and combustion stabilization obtained at hypersonic facility TsAGI T-131B. Tests are performed in nearly matched supersonic jet at the vicinity of the two-dimensional channel exit over range M=2.0-2.8 and stagnation temperature T_t= 1200-1400K. Initial thickness of jets is equal 67 mm.

2. Cold tests

One of possible schemes for generation of free recirculation zone in supersonic flow at vortex-bow shock wave infront of axyssimmetric diffuser working in unstart regime is given in Fig.1. That scheme was taken as a baseline at experimental verification of possibility of self-ignition and combustion stabilization using free recirculation zone.

Cold tests were conducted for refinement of vortex-generator and shock-generator geometry's and for investigation of influence of gas injection (with variation of mass rate and type of injection) into vortex. These tests are conducted in supersonic wind tunnels TSSM and SVS-2 TsAGI. Wind tunnels TSSM and SVS-2 TsAGI.

Wind tunnels TSSM and SVS-2 belong to type of blowdown facilities, working on the pressed air. Tunnels have nozzles of variable geometry, working chambers are closed, exhausting from working chambers is performed into atmosphere. Wind tunnel SVS-2 has dimensions large than tunnel TSSM.

During tests in TSSM vortex generator was installed upstream of diffuser at the nozzle flap and in SVS-2 at special rot (Fig.2). Angle of attack of vortex generation was changed over range α=0-10 degrees in tunnel TSSM and over range α=0-15 degrees in tunnel SVS-2. Shock generator was installed on special holder at distance x=130 mm downstream from vortex generator in TSSM and at x=175 mm in SVS-2. Mach number was M=2.5, Re_d =2.0-2.5 10^6 (d=50 mm is diameter of diffuser entrance).

Visualization of flow pattern was performed using schlieren device. Photographs of flow were taken too. At the diffuser entrance stagnation pressure was measured using Pitot probes

For gas simulator of fuel helium or air were used. Five variants of fuel supply were considered. In first four variants of gas simulator injection was performed through hole in pylon vortex generator, diameter of hole 0.7 mm. In fifth variant gas was

injected directly into interference zone through out tube of diameter 2 mm, which was mounted into diffuser. Mass rate of gas was varied by changing pressure in supply passage (maximum pressure was 2.5 MPa). Calculation of mass rate was done under assumption of sonic velocity at the hole.

Analysis of flow pictures in the interference region of vortex and shock wave and total pressure field [12] showed, that for all variants of gas injection pressure level inside of recirculation zone is close to limit pressure at boundary layer separation from surface. Injection of gas both into vortex and directly into recirculation zone did not change character of flow in the interference region and did not break recirculation zone. It has to be stressed that these conclusions are obtained for quite modest range of pressure in gas supply passage. As future tests in high-enthalpy flow showed (where pressure in supply passage was large, up to 10 MPa) gas injection into vortex can to weak vortex and, in some cases, to complete disappearance of a free recirculation region.

3. Tests in high-enthalpy flow

3.1. Estimation of minimum dimension of recirculation zone for self-ignition and combustion stabilization.

Let's evaluate the minimal necessary size of a free recirculation zone, which is required for fuel-self ignition and stabilization of combustion. For this evaluation we use criterion of combustion stabilization behind a bluff body in subsonic flow of homogeneous fuel mixture (see, e.g. [9,15-17])

$$\tau_{res} / \tau_{ind} \approx 1,$$

where τ_{res} and τ_{ind} are residence time and induction time, respectively.

In experiments [9] it was shown that this criterion is applicable for both a supersonic flow and a diffusion combustion (i.e. in those cases where composition of

the fuel mixture varies greatly over the volume of flow). Residence time can be roughly estimated by equation [9,15-17]

$$\tau_{res} = k\, h/u_e$$

where k= 30-50, h is maximum width of the recirculation zone, u_e is velocity at the boundary of the recirculation zone (i.e. behind the conical shock). Estimation for T_t=1200-1400 K and M=2.5 gives u_e=1000 m/s. We would like to point out that value of k=50 in the last equation was the result of experiment [16], where residence time was measured in a base flow region of an axisymmetric body at M=4.1.

For the estimation of induction time we assume static temperature inside the recirculation zone equals total temperature (this assumption is based on the fact that velocities inside the zone are quite low). Another assumption is that static pressure inside the recirculation zone is equal to atmospheric pressure. For T_t =1200K and 1400K and atmospheric pressure induction times for stoichiometric kerosene-air mixture are [15,18], respectively $\tau \approx 5\cdot10^{-3}$ s and $3\cdot10^{-4}$ s (for the hydrogen-air mixture $\tau \approx 5\cdot10^{-5}$ s and $1\cdot10^{-5}$ s respectively). Hence, for the stabilization of combustion of kerosene-air mixture in the recirculation zone it is necessary that the width of recirculation zone were greater than

$$h > h_{cr} \approx u_e \cdot \tau_{ind} / k,$$

where at T_t =1200K

$$h_{cr} \approx 10 - 16\text{sm}$$

and at T_t =1400K

$$h_{cr} \approx 0.6 - 1\text{sm}.$$

In our experiment entrance diameter of the diffuser (shock-generator) was *d*=25mm. It is known, that the width of recirculation zone (h) is almost the same as *d* [1-3]. Thus we can expect the self-ignition and stabilization of combustion in our tests to occur only starting from 1400K. It is expected that when fuel, which is coming to

the recirculation zone from the external supersonic flow (kerosene) or injected directly into the recirculation zone (hydrogen), self-ignites in this zone, and the zone would play a role of an ignition and stabilization source for combustion of kerosene-air mixture in the main supersonic flow.

3.2. Scheme of the experiment. Facility and tests conditions.

Experimental research on supersonic kerosene combustion stabilization were conducted on T-131B facility, used for supersonic combustor connected pipe tests . The air flow was pre-heated by kerosene combustion with extra injection of oxygen (vitiated air). Vitiated air parameters in the pre-heater: $T_t = 1000 - 2300$ K, $P_t \leq$ 10 MPa. The test facility is equipped with rectangular nozzles designed for M=2.5; 3.0 and 3.5 with exit cross section 30x100 mm^2 . Scheme of the experiment on free recirculation zone self-ignition and stabilization of combustion of kerosene barbotaged with gas in high-enthalpy supersonic flow is presented in Fig.4.

Supersonic flow with Mach number in the range M=2.0-2.8 and cross-section of 60x100 mm^2 is created at the exit of a rectangular divergent channel (3) which is connected to a rectangular nozzle (1) designed for M=2.5. The jet is exhausted into the quiet atmosphere. During test runs the parameters at the channel exit are supposed to keep at the level to have a matched jet.

Free recirculation zone is to be created by interaction between trailing vortex (11), generated by a vortex generator (4) installed in the channel, and detached bow wave in front of the diffuser (5), which is placed downstream the flow.

3.3. Experimental model

3.3.1. 2-D channel and fuel injectors

Experimental model scheme, which includes rectangular channel (3), injectors (2), pylon-vortex generator (4), diffuser (shock-generator) (5), transversing equipment (6),

is shown in Fig.5. The rectangular divergent channel (3) used in this experiment consists of two sections. Front section with length of 300mm and rectangular cross-section of entrance $30x100mm^2$ diverges along bottom wall with an angle of half degree. Second section with length of 500mm diverges along both, bottom and top walls with an angle of 2 degree and has cross-section of exit $67x100mm^2$. Estimations have shown that with these dimensions of channel exit it is possible to get the flow core with practically uniform velocity and size of 35-40mm.

Kerosene-air mixture at exit of the channel is created by mixing of gas (air, hydrogen) barbotated kerosene and air. Kerosene is supplied perpendicular to the main flow through holes drilled in walls of four tube injectors (2), which are installed at 70mm from the channel entrance. Tube injectors have height 30mm and thickness 3mm. They are mounted on the lid of a hatch across the channel. Each of the four injectors has 3 holes (d=0.6mm) on each side, which play role of nozzles (Figs. 5-7). The distance from injectors to channel exit is about 1m, thus kerosene-air mixture is nearly homogeneous at the channel exit.

3.3.2. Barbotage of kerosene

Barbotage is carried out in the specially designed mixing device, which provides a kerosene-air mixture with mass rate ≤ 0.25 kg/s and weight percentage of gas in the mixture less than 5% (Fig.8). Using of barbotage allows to organize better spay and mixture of kerosene with supersonic flow efficiency of barbotage is illustration in Fig.9a,b. Fig.9a - pure liquid kerosene, Fig 9b - barbotage kerosene. It is seen that expanding angle of the second jet is noticeably greater than of the first one.

3.3.3. Vortex generator

In order to generate a trailing vortex a vortex-generator is used. Vortex generator has a shape of an pylon and is mounted on the hatch lid of rectangular channel (section 2) at 50mm before the exit (Fig.5,10,11).

Schematic plot of vortex generator, which was developed basing on research [12,13] is shown in Fig.10. The vortex generator (1) is semispan wing having a diamond shape airfoil section with a chord length of - mm a span of , mm, a half-angle of degrees, and angle of attack capability in the range. The dimensions of vortex generator are specifically chosen to get an intensive trailing vortex in the core of the supersonic flow at the exit of diverging channel. Vortex generator is mounted on the wall of the channel (2). In order to control the intensity of the trailing vortex a possibility of changing an angle of attack is foreseen. The construction of vortex generator has a cooling duct (3) to cool it during start-up of the test facility. This duct is also used to supply hydrogen (or another fuel) into recirculation zone. Components required can come to the duct through out a special connecting pipe (4) and leave it through the hole of diameter (5) 1mm, which is placed at the back edge of vortex generator. To provide the durability of generator under high temperatures and pressures it is produced from a strong alloy steel.

3.3.4. Shock wave generator

Schematic plot of baseline diffuser (shock generator) is given in Fig.12 and its photography in Fig.13. Diffuser channel is axisymmetrical with typical parts: supersonic diffuser, throat and subsonic diffuser. As mentioned above, the dimensions of the diffuser were specifically chosen to get the volume of recirculation zone, emerging as the result of interaction between trailing vortex and detached bow shock in front of the diffuser, sufficient to provoke self-ignition and combustion stabilization inside of the zone.

Diffuser is fixed in a special holder (3) which is mounted on the stand of transversing equipment (4). Transversing equipment allows to move the holder with the diffuser in and out of the desired region of the flow during a test run.

Diffuser has a sharp edge lip. Relation between throat area entrance and diffuser area was chosen according to the recommendations of work [19]. This relation

secures the start of the diffuser in supersonic flow with $M>2.1$ and when trailing vortex goes into the diffuser. Inside the construction of the diffuser one can find a throttling hollow (5), which is connected to the diffuser's throat by six holes (6). The holes are spread evenly across the circle of the channel's cross-section and are 1.5 mm in diameter. To achieve the gas-dynamic throttling of the diffuser gas (or fuel) can be supplied into the throttling hollow through the connecting pipe (7). Gas-dynamic throttling allows to vary effective throat area of diffuser, if necessary. This gives a possibility to change from start to unstart regimes at any velocity of main flow. During test runs static pressure along channel walls is measured in three points (8), situated on supersonic diffuser, throat and subsonic diffuser. A possibility to change the lip (9) is foreseen in a case it is damaged while testing, or if geometrical parameters of the diffuser are to be altered.

To ensure operation under high temperatures and loads the holder and constructions of diffuser are made of endurable steel, and its lips are from heat-resistant steel.

Photography of diffuser is given in Fig.13, in Fig.14 photography of diffuser mounted on transversing equipment is presented.

During first tests with combustion stabilization diffuser was damaged. Simplified conduction diffuser was designed and manufactured. The scheme of this diffuser is given in Fig.15. Photography of simplified diffuser is presented in Fig.16, in Fig.17 photography of diffuser mounted on transversing equipment is presented.

3.4. Tests methodology

3.4.1. Generation of recirculation zone

At the beginning of the test program the conditions of origination of the free recirculation zone were found. These runs were done with the total flow temperature T_t =1200K for two cases: 1) with kerosene injectors; 2) without kerosene injectors. In the second case the fuel is not supplied into the injectors in order to estimate the

conditions of originating of the free recirculation zone several parameters are varied: angle of attack of the vortex generator, distance between the vortex generator and the diffuser, throttling intencity. Besides, the influence of air or hydrogen injection through out the vortex generator on the initiation of the free recirculation zone is investigated. The experiments are conducted in the following order:

- cold air starts blowing through out the injectors and through out the vortex generator in order to cool them
- measurement equipment system is switched on
- the preheater is switched on and the designed regime is reached
- transversing equipment moves the diffuser into the designed location in the flow
- the diffuser (shock generator) is throttled
- air blowing through out the pylon-vortex generator is shut off for 2-3s
- during this time hydrogen is supplied through the pylon-vortex generator under the designed pressure
- hydrogen supply throughout the pylon-vortex generator and kerosene supply into the preheater are shut off.

3.4.2. Tests on self-ignition and combustion stabilization

Investigation of gas (air) barbotated kerosene self-ignition and combustion stabilization were conducted after the conditions of free recirculation zone originating are known. The test runs were done with the total flow temperature in the range of T_t=1200-1400K.

The minimum T_t is estimated which still allows the stable combustion in the recirculation zone. Here is the proposed experiment procedure:

- cold air starts blowing through out the injectors and through the vortex generator in order to cool them;
- measurement equipment system is switched on
- the preheater is switched on and the designed regime is reached

- transversing equipment moves the diffuser into the designed location in the flow
- barbotated with gas kerosene is supplied through out the injectors
- the diffuser is throttled
- air blowing through out the pylon-vortex generator is shut off for 2-3s
- if self-ignition and combustion does not occur, hydrogen is supplied through out the pylon-vortex generator under the designed pressure to promote ignition - after 2-3 seconds hydrogen supply throughout the pylon-vortex generator and kerosene supply into the preheater are shut off.

3.4.3. Measurements

During the test runs the following measurements were taken:

1. Axial static pressure distributions along on the top and bottom walls of the rectangular channel.
2. Axial static pressure distribution on the wall of diffuser .
3. Preheater pressure
4. Air, hydrogen, and oxygen pressures and temperatures before their flow-meter nozzles
5. Pressure and mass-rate of kerosene before the barbotage-mixer
6. Fuel mixture pressure before the injectors
7. Pressure of hydrogen (air) supply into the vortex generator
8. Pressure of the throttling air in the diffuser
9. Videotaping of the flow at the exit region of the rectangular channel made through schlieren instrument
10. Videotaping of the flow at the exit of the rectangular channel and videotaping of the fuel mixture spray from the nozzles (while calibrating)

The measurement scheme is shown in Fig.18, the photography of the Schlieren instrument is shown in Fig.19.

Pressure measurements are done with IKD- and DDM-type sensors with the accuracy of ±0.5%.

3.5. Experimental results

List of runs and conditions at which they were conducted are given in the table.

3.5.1. Total pressure fields at the vicinity of channel exit

Stagnation pressure fields at the vicinity of the channel exit with injectors and without injectors were measured in runs No 1 and No 2. Parameters at the channel entrance: $M = 2.5$, $P_t = 4.0$MPa, $T_t = 1400$K. Measurements are done at distances 18mm and 50 mm from exit.

Stagnation pressure was measured by scanning horizontal ten-point rake, which was vertically moved by transversing equipment. Figs 20, 21 present axial pressure distributions on channel walls for runs No1, No2, respectively and also stagnation pressure fields in the flow core at distances 18 mm and 50mm from the channel exit respectively.

Two conclusions can be drawn from Figs 20,21:

1) static pressure on walls closely to channel exit is within range 0.8-1.1 Bar, e.g. jet is matched to atmosphere

2) stagnation pressure variation inside of jet in vertical direction within range 19 mm $<y<$48mm (see reference system in Figs 20,21) is negligible and, so the core thickness is about 30 mm. M numbers, calculated on the base of measured stagnation pressure and static pressure equal 0.1 MPa are within range M=2.5-2.8 and M=2.57-2.85 at distances 18 mm and 50mm, respectively.

Beginning from run No5 4 tube injectors were installed in to channel (Figs 5-7). Installation of injectors results in 1.5 time increase of static pressure at the end of channel (see, e.g. axial pressure distributions for run No7, Fig.28) in comparison with runs No1, 2 in which injectors were absent. Stagnation pressure fields at the vicinity

of channel exit in runs No5-No11 were not measured, but rough estimation shows, that injection installation results in decease of Mach number down M=2 at distance x=18mm from exit. For matched condition to obtain at the channel exit in this case it is needed to decrease pressure in preheater to Pt =2.7 MPa.

3.5.2. Generation of shock wave

In run No3 methodology of bow shock wave generation was refined. Run was performed without injectors and vortex generator. Diffuser was located at distance 50 mm downstream of channel exit. Flow parameters at the channel entrance: M = 2.5, P_t= 3.9MPa, T_t = 1200K. Fig. 22 shows axial pressure distributions on channel walls, and also on diffuser walls for two cases

1) without diffuser throttling

2) diffuser throttling, using air jets in the diffuser throat. Figs 23a, b give Schliren pictures of flow field infront of the diffuser. It is seen from Fig.23a that flow in supersonic inside of diffuser for the case without throttling. Bow shock is generated infront of diffuser for the case with throttling. Pressure rise roughly corresponds to M=2.5. Subsonic flow behind of bow shock wave is accelerating and reaches sonic velocity at the throttling section (Fig.22).

3.5.3. Generation of free recirculation zone

Test on generation of free recirculation zone was performed in run No4. Flow parameters at the channel entrance are P_t=3.9MPa, T_t =1200K. Test was done without injectors, but with vortex generator and diffuser with throttling of last. Angle of attack of vortex generator was 15 degrees. It was installed at distance about 50mm upstream from channel exit. Diffuser was installed at distance about 50mm downstream from channel exit. Axial pressure distributions on channel walls and diffuser wall and Schliren pictures are presented in Figs. 24, 25a, b, respectively. Two cases were considered

1) with air supply into pylon-vortex generator

2) without air supply into pylon vortex generator.

In first case air mass rate was 1.5 g/s (pressure supply 1.0 MPa). It is seen from Fig. 25a, b that in both cases free recirculation zone arise infront of diffuser. But dimension of recirculation region is greater for the second case (compare Figs 25a and 25b). Thus, this test shows that injection of high pressure gas into vortex results in decrease of vortex intensity, the decrease of dimension of recirculation zone is a consequence of that. It can be a assumed that some critical valve (dependent of course, on shock intensity and vortex structure) of air mass rate, when breakup of vortex tatus place. In this case interaction of vortex with shock is reffered as weak (see [1]), and only bending of shock is realized during interference. Unfortunately, this interesting problem is outside of our investigation.

3.5.4. Non self-ignition and combustion stabilization at T_t =1200K, 1300K.

No self-ignition was obtained at runs No 5, No 6, where stagnation temperature was, respectively T_t =1200K, 1300K. During these test and also all following, where stabilization was studies, kerosene was supplied in front section of rectangular channel at distance 70mm from entrance (Fig.5-7) throughout tube injectors. Kerosene, barbotaged by air was injected in tests No5, No6. Mass air concentration in kerosene - air mixture needed for stabilization (see. 3.1).

3.5.5 Self-ignition and combustion stabilization of barbotaged kerosene at T_t=1400K.

Self-ignition and combustion stabilization of barbotaged kerosene was obtained in run No 7, at T_t =1400K. Time development of self-ignition process was run as follows. First of all (see description in 3.6.3) free recirculation zone was organized in supersonic flow(photography in Fig.26a). Afterwards supply of barbotaged kerosene throughout was performed, and hydrogen was injected throughout vortex generator.

Fuel equivalence ratio was ER=0.7, mass rate of H_2 was 0.5 g/s. Quickly in some region of free recirculation zone self-ignition arise following by propagation of flame throughout all free - recirculation zone and at final stage outward of zone to supersonic flow of kerosene-air mixture (photography in Fig. 26b). Upstream propagation of flame was not observed. Approximately 3s after beginning of kerosene supply diffuser and holder were thermally damaged (photography in Fig. 27). Character of thermal damage of diffuser (Fig. 27) gives evidence of intensive heat release in front of and in vicinity of diffuser.

Damage of holder was evidently due to fall on it of conic shock wave from recirculation region. Axial pressure distributions on channel walls are given in Fig. 28.

3.5.6. Self-ignition and combustion stabilization of pure kerosene at T_t=1400K

In runs No 8, No 9 efforts were undertaken to obtain self-ignition of pure liquid kerosene, at the same temperature T_t=1400K as in run No 7. Fuel equivalence ratio ER was about ER=1.5. Since baseline diffuser was damaged in last run, the simplified construction diffuser was used in this run. Diffuser was installed at distance 25 mm downstream of the channel exit. In run No 8 air was supplied throught vortex generator together with kerosene supply throughout tube-injectors. In run No 9 after some time air supply was switched off, and H_2 was injected throughout vortex generator. Axial pressure distributions on channel walls in runs No 8, No 9 are plotted in Figs 29, 30, respectively. In runs No 8, No 9 radiation was observed mainly from recirculation zone (photography in Fig. 31, run No 8), without intensive burning in external supersonic flow as was in run No 7 with barbotaged kerosene. Possible reason of such a moderate combustion is explained by worsening of mixing between kerosene and air without barbotage.

3.5.7. Role of shock wave

Last two runs No 10, No 11 were directed to learn the role of shock wave in the stabilization. To this end runs No 10, No 11 were conducted without vortex generator and, consequently, without recirculation zone, but only with bow shock infront of diffuser. Tests were performed at two stagnation temperatures T_t=1200K (run No 10) and T_t=1400K (run No 11), P_t=2.7 MPa. Axial pressure distributions on channel walls for runs No 10, No 11 are presented in Figs 32, 33, respectively. Simplified construction diffuser was used (see 3.3.4). Tests showed absence of self-ignition of barbotaged kerosene in diffuser region for start regime and unstart (with bow shock due to air throttling), Figs 34a, b, run No 11. At T_t=1400K auto-ignition was observed in far region downstream of diffuser. Thus, it can be concluded that self-ignition of kerosene-air mixture was realized only due to free recirculation zone in front of diffuser.

4. Conclusions

1. Practically realizable scheme of combustion stabilization in supersonic flow using free-recirculation zones generated by concentrated vortex-bow shock interference is proposed.
2. Aerodynamic model for experimental confirmation of combustion stabilization scheme for barbotaged kerosene in supersonic flow of hypersonic facility TsAGI T-131B is designed and manufactured.
3. Dimensions of aerodynamic model are chosen to realize self-ignition and combustion stabilization. Criterion of stabilization of flame in the wake of bluff body was used. It was proven that dimensions of T-131B facility allow to obtain self-ignition and combustion stabilization of barbotaged kerosene at stagnation temperature T_t=1400K.
4. Experiments confirmed principles on which design of model was performed and dimensions of it.. At T_t=1400K self-ignition and combustion stabilization of

barbotaged kerosene was obtained in nearly matched supersonic jet by using free separation zone generated by concentrated vortex-bow shock interference. Outward combustion propagation into supersonic flow was obtained (without upstream propagation). Self-ignition of pure liquid kerosene takes place only inside of free recirculating zone without outward propagation into supersonic flow.

5. Self-ignition and combustion stabilization of barbotaged kerosene in free recirculating zone at T_t=1200K-1300K is absent.
6. It is shown that injection of gas into vortex results in weaking of concentrated vortex and, as a consequence, decrease of dimensions of free recirculation zone. Hypothesis is put forward that limiting value of injection mass rate exists and excess of which free recirculation zone disappears.

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Table

Tests Conditions, Objectives and Results of tests

Run number	P_t, MPa	T_t, K	M_{ent}	ER	Objectives and results
No1	3.85	1418	2.5	0	Stagnation pressure fields at supersonic jet at distance x=18mm and x=50mm from the channel exit are measured
	3.81	1408	2.5	0	
	3.79	1403	2.5	0	
	3.81	1402	2.5	0	
	3.83	1407	2.5	0	
No2	3.87	1433	2.5	0	
	3.90	1441	2.5	0	
	3.87	1425	2.5	0	
	3.89	1429	2.5	0	
	3.87	1424	2.5	0	
No3	3.95	1197	2.5	0	Bow shock in front of the shock wave generator is obtained
	3.93	1194	2.5	0	
No4	3.91	1187	2.5	0	Free recirculation zone in front of the shock wave generator as a result of vortex and bow shock interference is obtained
	3.91	1192	2.5	0	
	3.88	1185	2.5	0	
No5	2.75	1220	2.5	0	No self-ignition and combustion free stabilization of barbotages kerosene in recirculation zone
	2.76	1210	2.5	1.23	
No6	2.75	1280	2.5	0	
	2.72	1275	2.5	0.77	
No7	3.80	1400	2.5	0	Self-ignition and combustion free stabilization of barbotaged kerosene in recirculation zone is obtained. Outward propagation of combustion take place
	3.82	1407	2.5	0	
	3.80	1401	2.5	0	
	3.79	1396	2.5	0.7	
No8	3.93	1433	2.5	0	Self-ignition and combustion outward stabilization of kerosene in free recirculation zone is obtained. No propagation of combustion.
	3.94	1436	2.5	0	
	3.92	1423	2.5	1.46	
No9	3.97	1461	2.5	0	
	3.96	1453	2.5	0	
	3.97	1460	2.5	1.56	
No10	2.53	1190	2.5	0	Role, plaied alone by bow shock, in combustion stabilization is studied. It is shown that self-ignition is absent.
	2.54	1190	2.5	0.51	
No11	2.66	1384	2.5	0	
	2.69	1406	2.5	0.9	

M_{ent} - Entrance Mach number
P_t - total pressure at the channel entrance
T_t - total temperature at the channel entrance

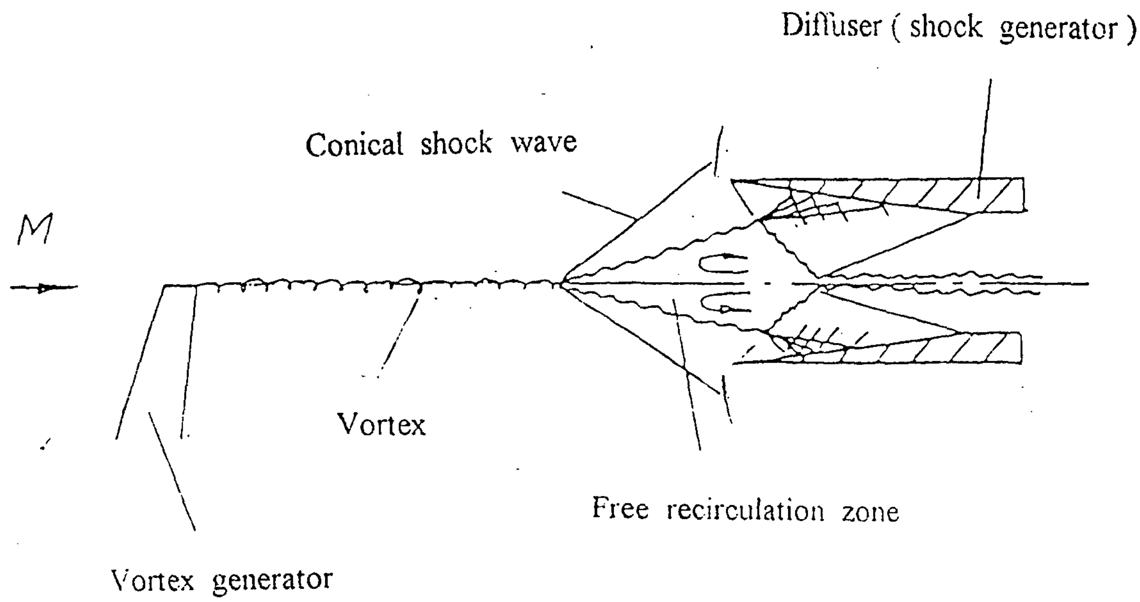

Fig.1 Schematic of flow-field and experimental facility

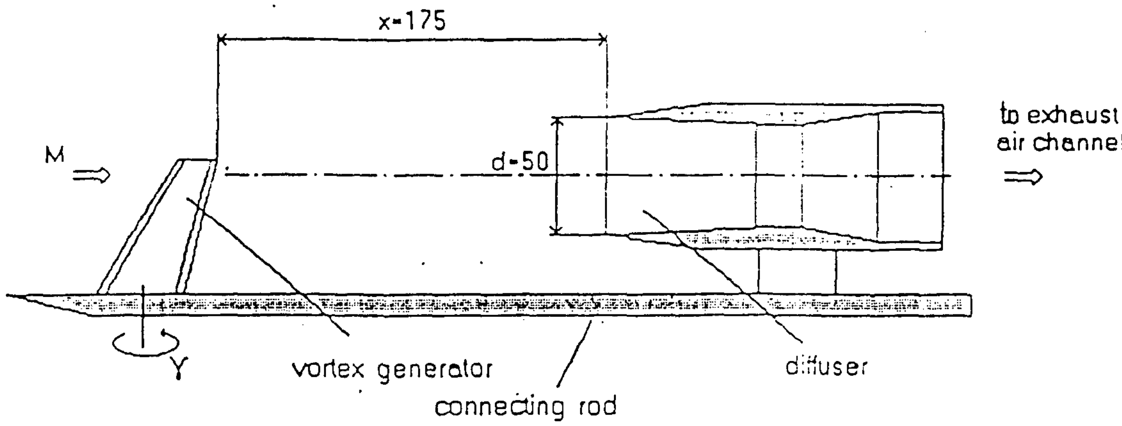

Fig.2 Installation of the vortex generator and diffuser (shock generator) in the facility

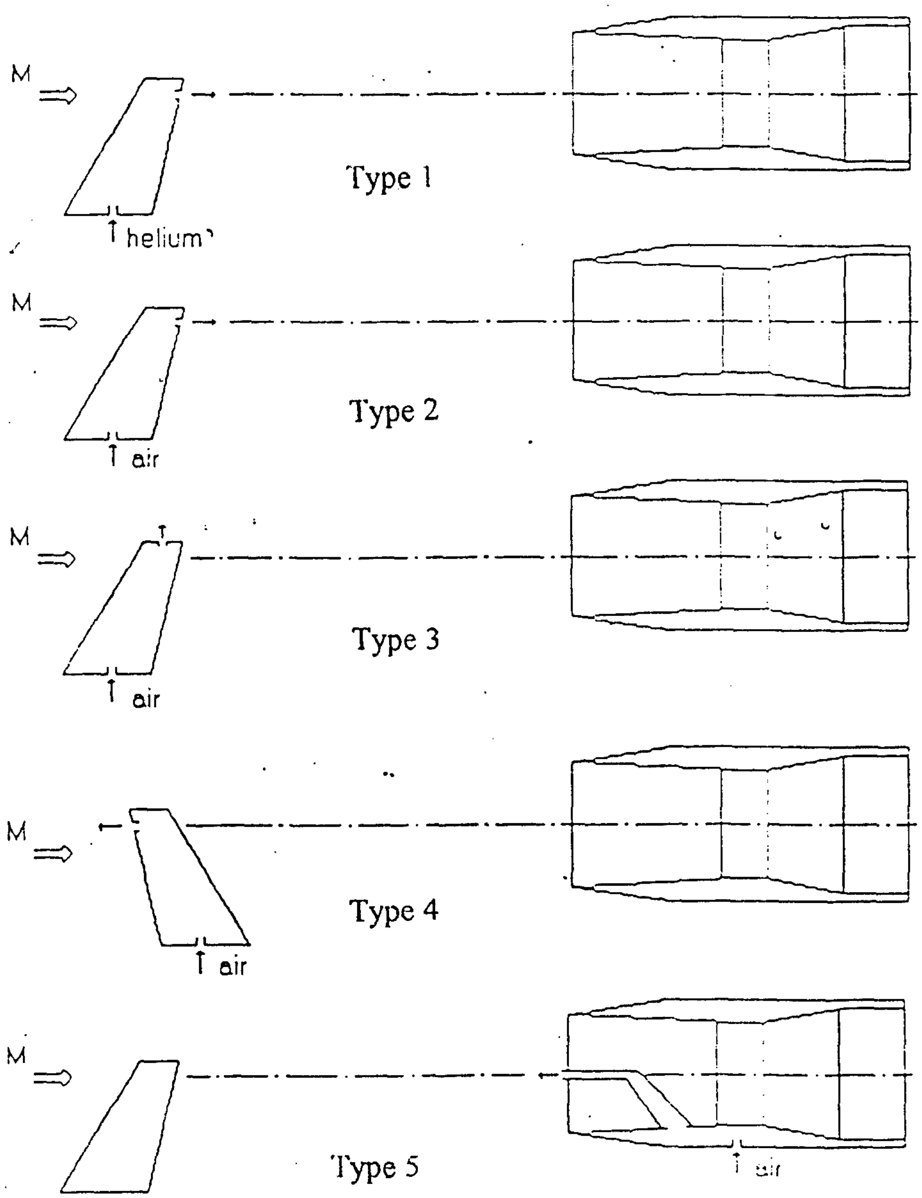

Fig.3 Types of fuel supply through the vortex generator

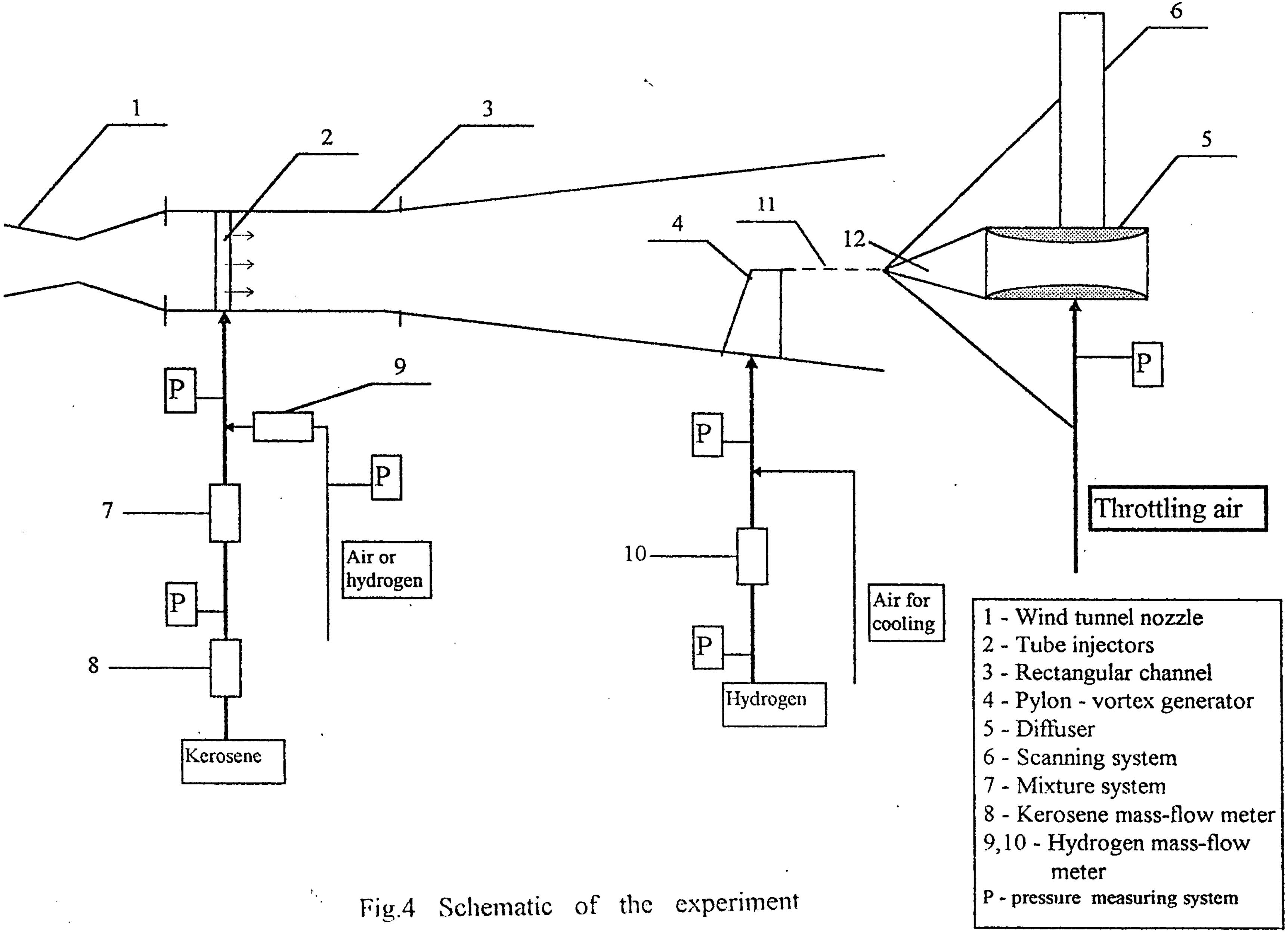

Fig.4 Schematic of the experiment

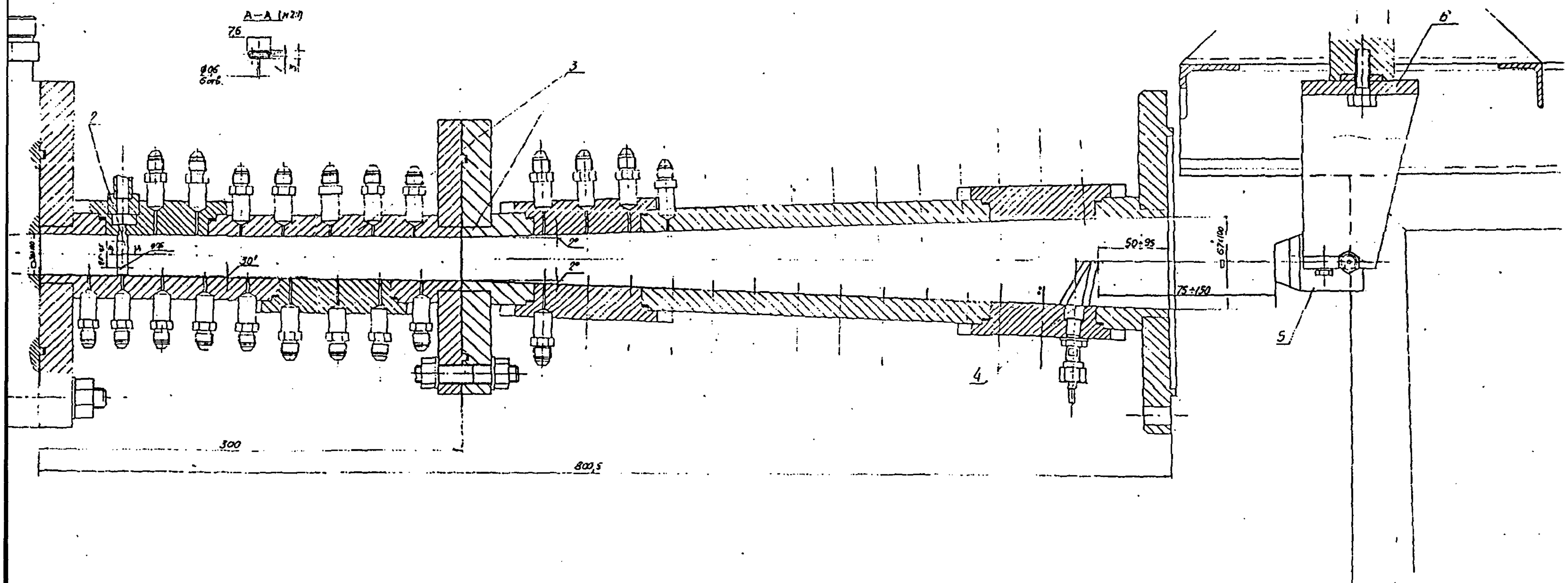

Fig.5 Schematic of the experimental model

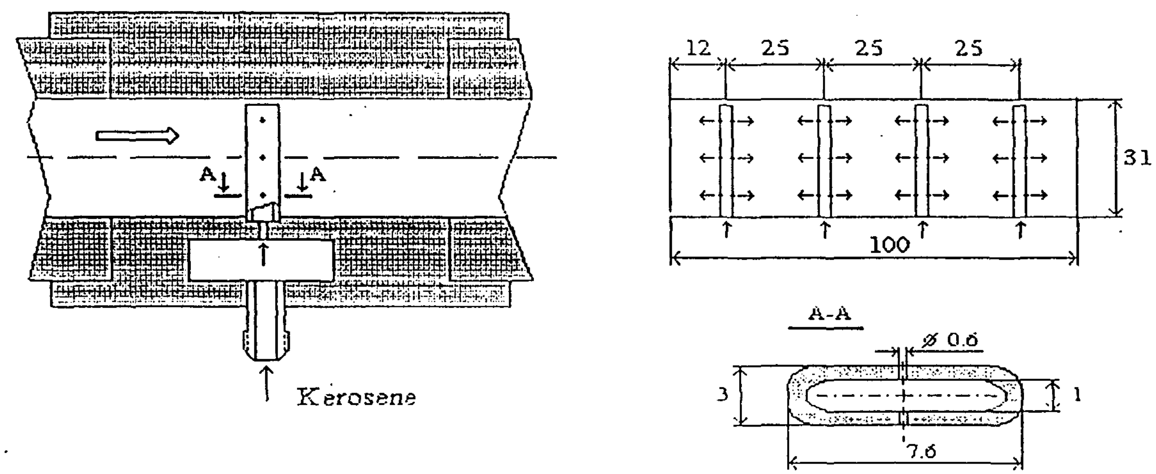

Fig.6 Tube - injectors location

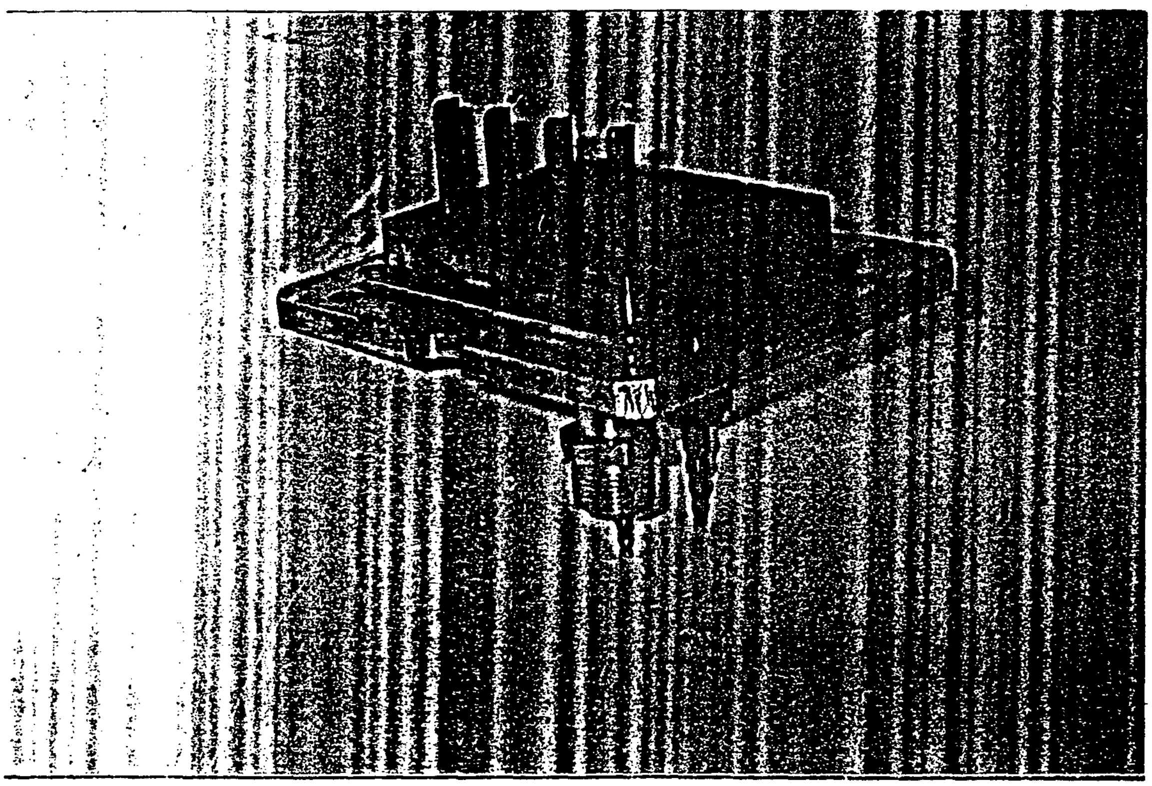

Fig.7 Photography of the tube - injectors

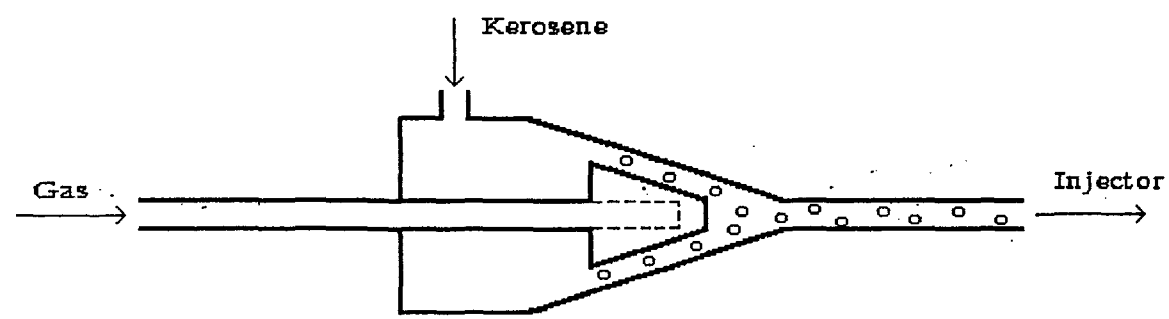

Fig. 8 Schematic of the mixture system (barbotage device)

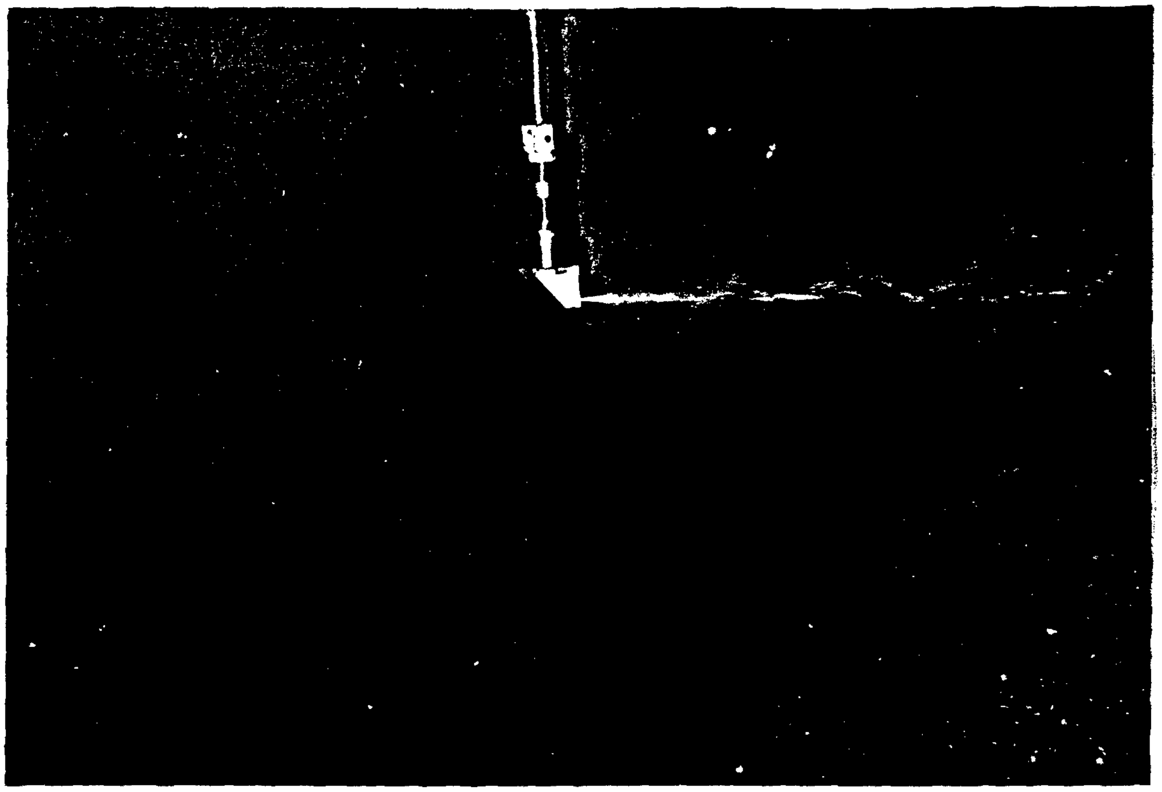

Fig.9a Photography of the jet of liquid kerosene

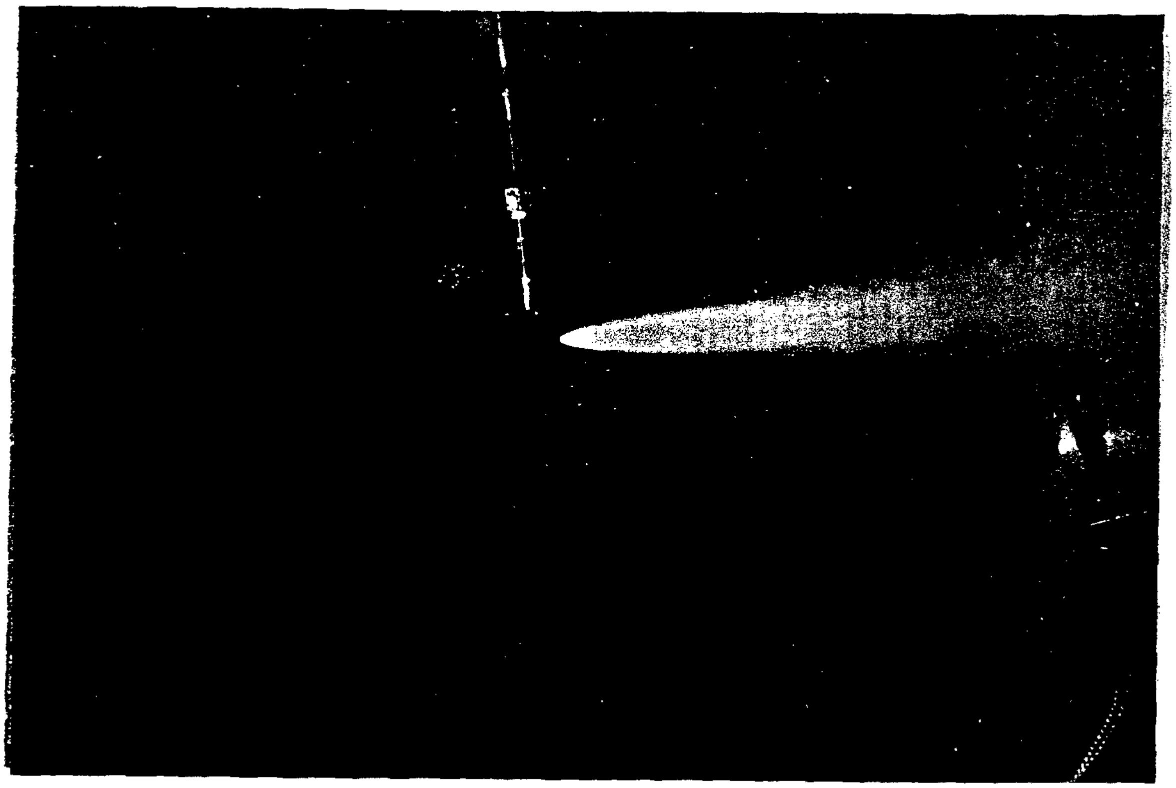

Fig.9b Photography of the jet of kerosene barbotaged by air

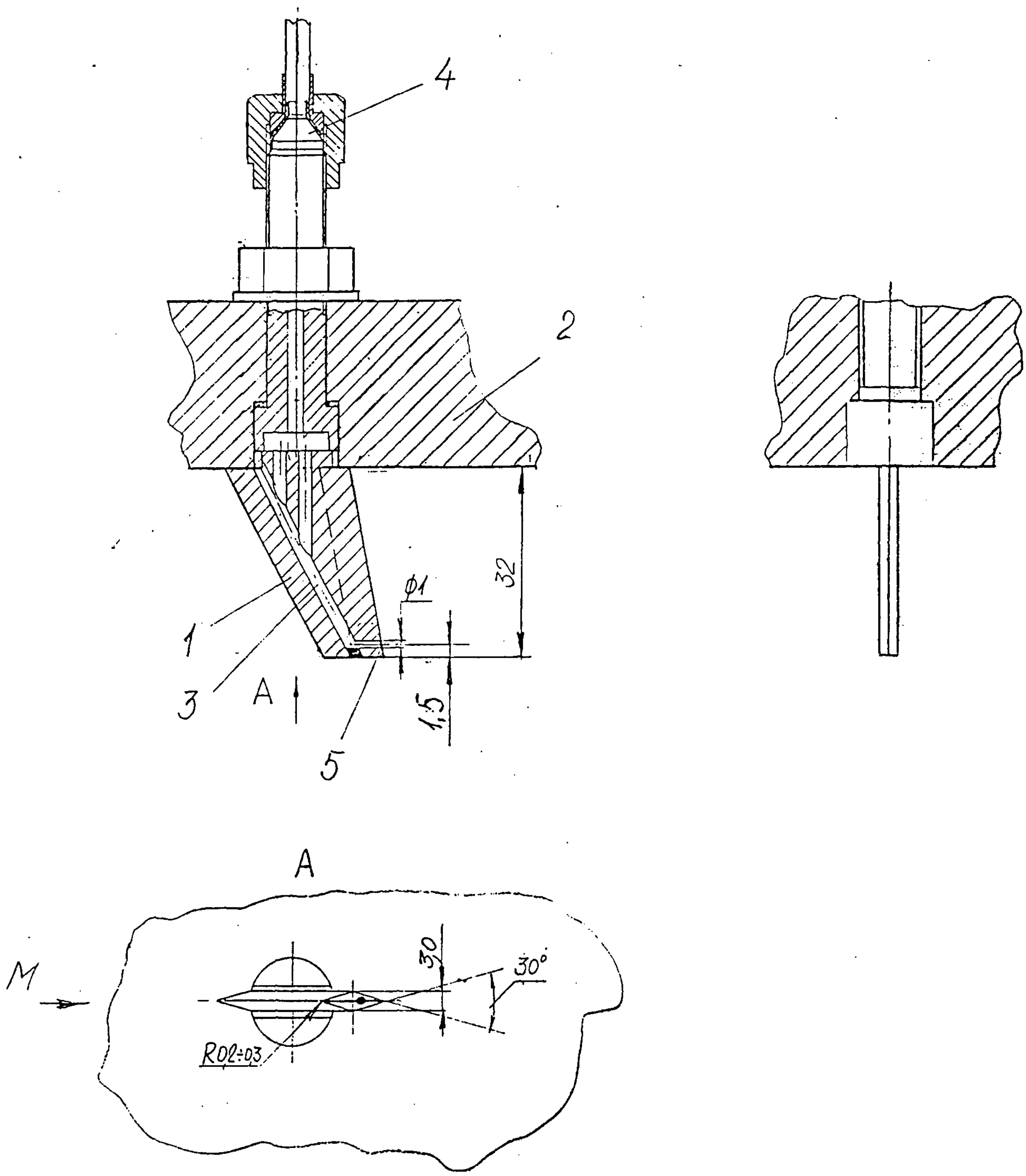

Fig.10 Schematic of the vortex generator

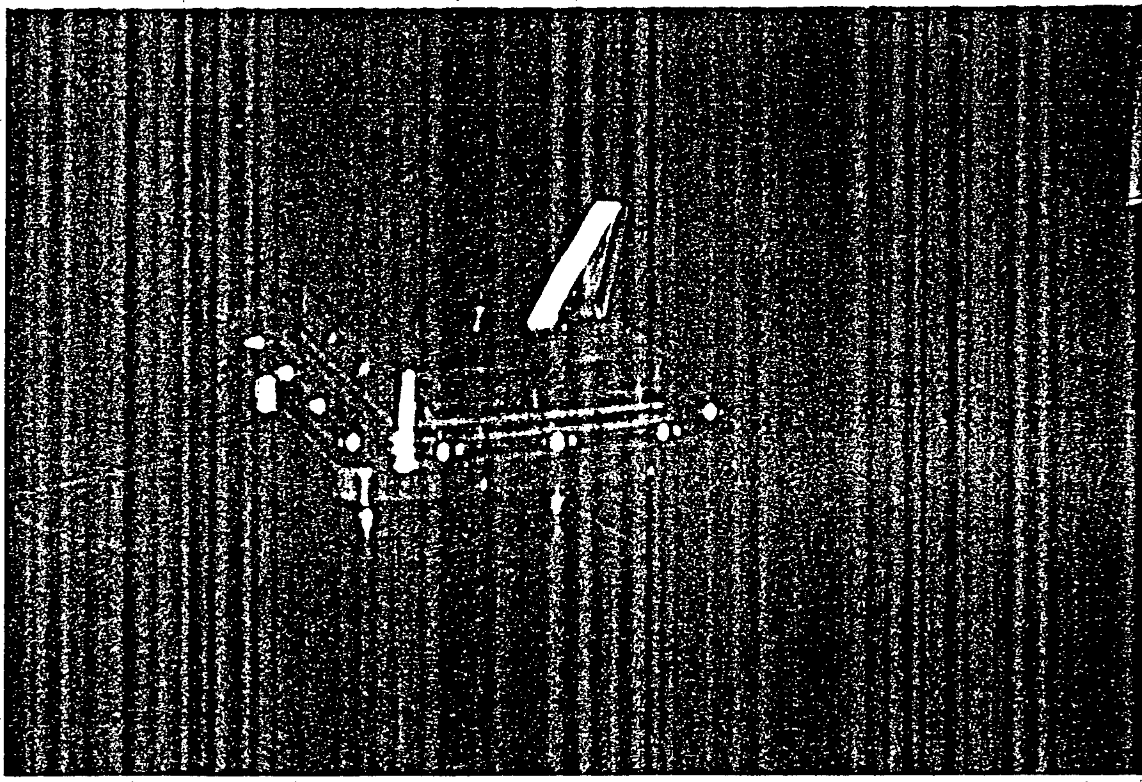

Fig.11 Photography of the vortex generator

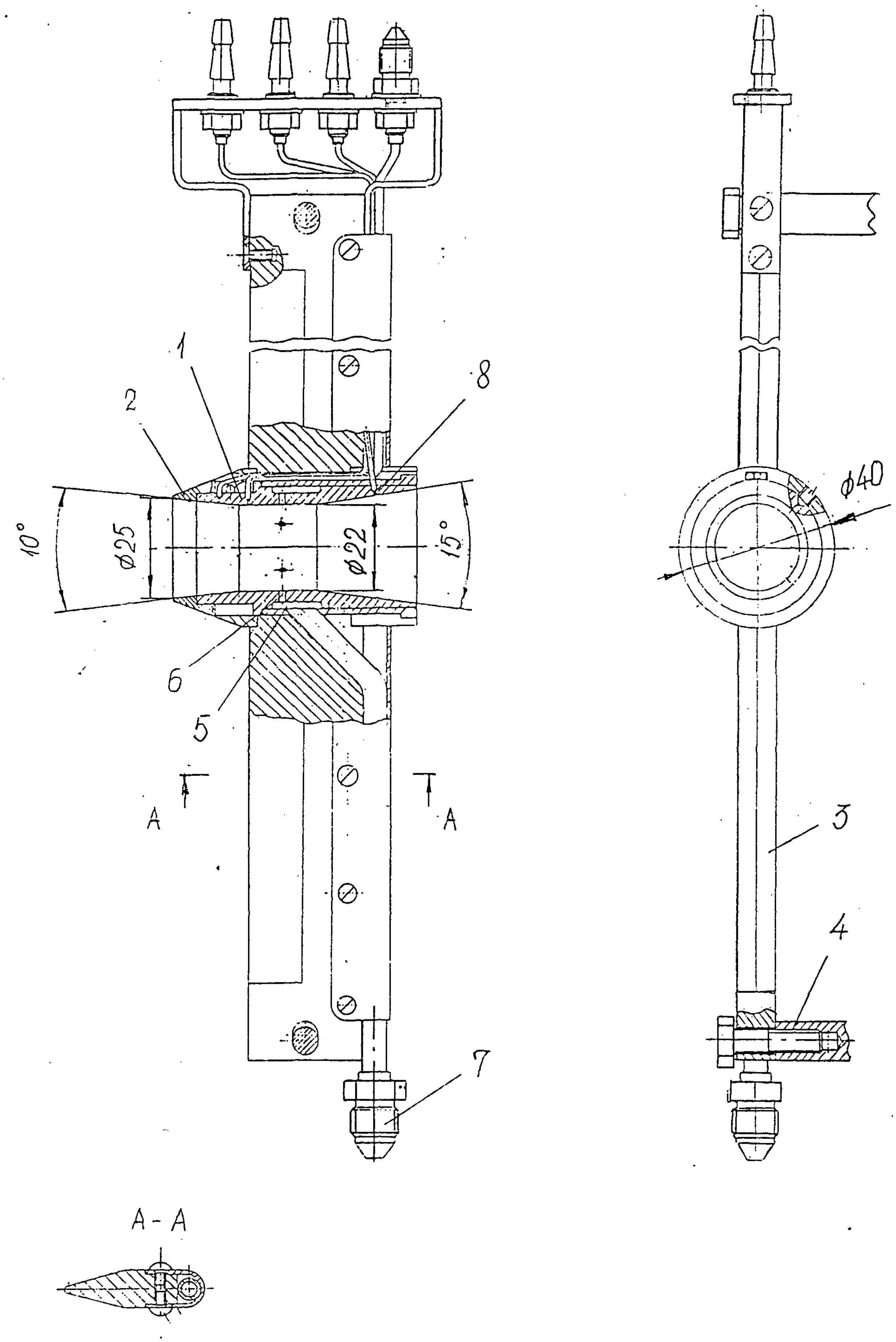

Fig.12 Schematic of the baseline diffuser (shock generator)

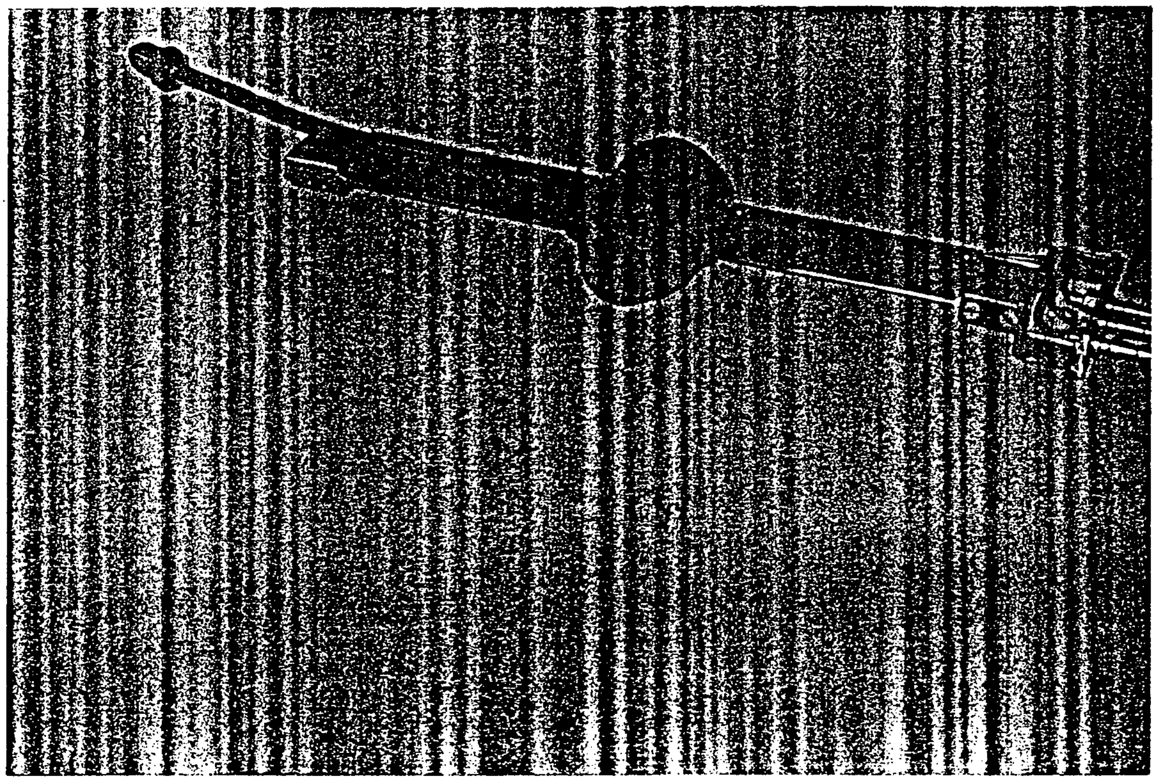

Fig.13 Photography of the baseline diffuser

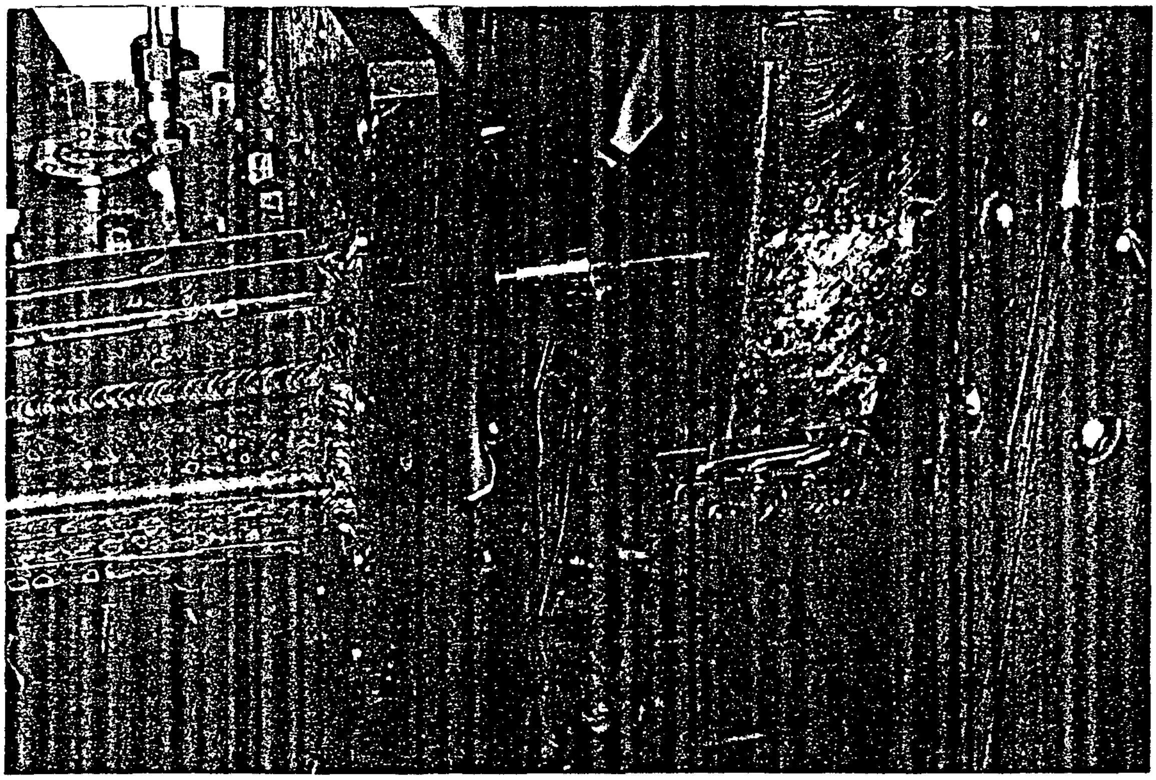

Fig.14 Photography of the baseline diffuser installation on the transversing equipment

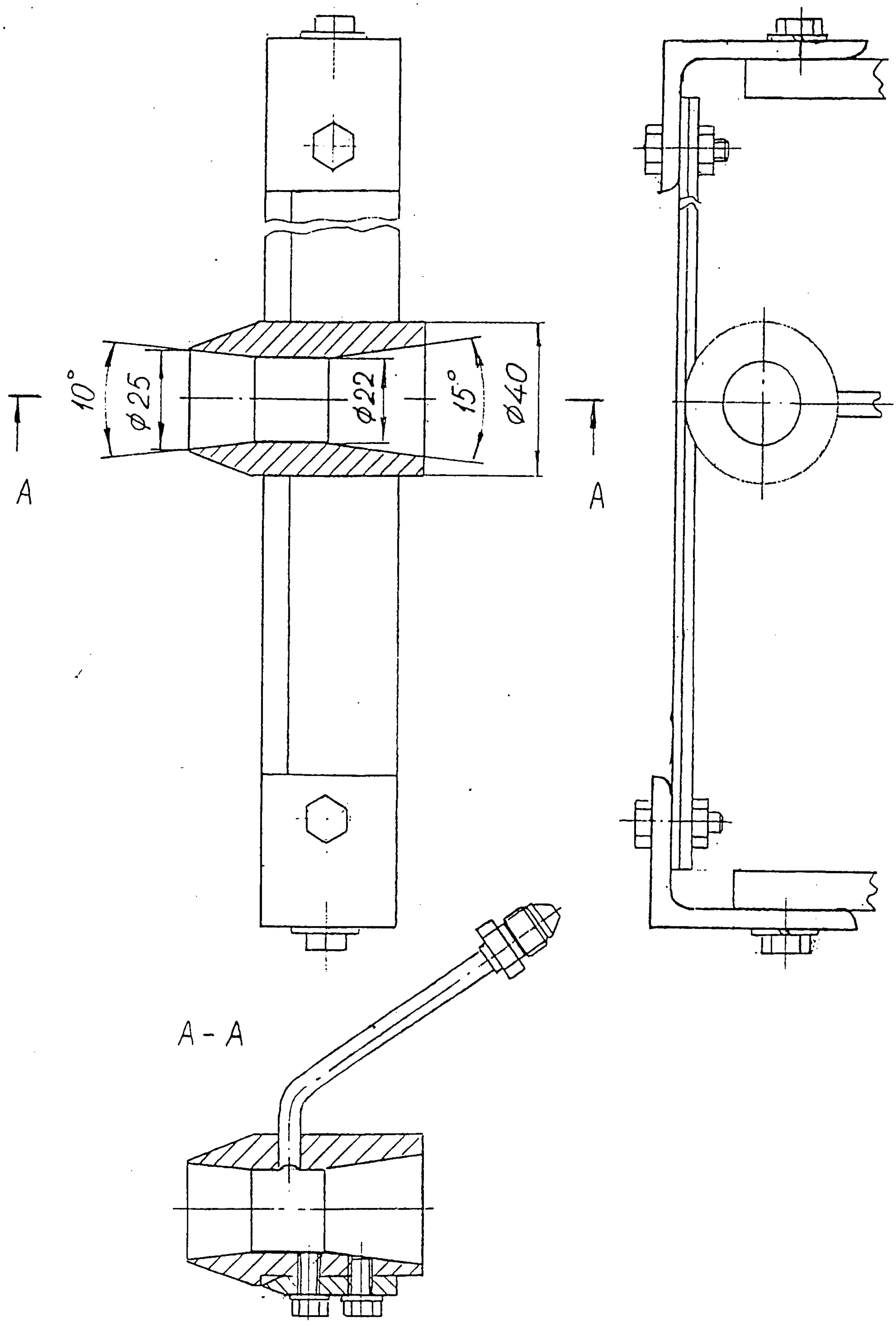

Fig.15 Schematic of the simplified construction diffuser

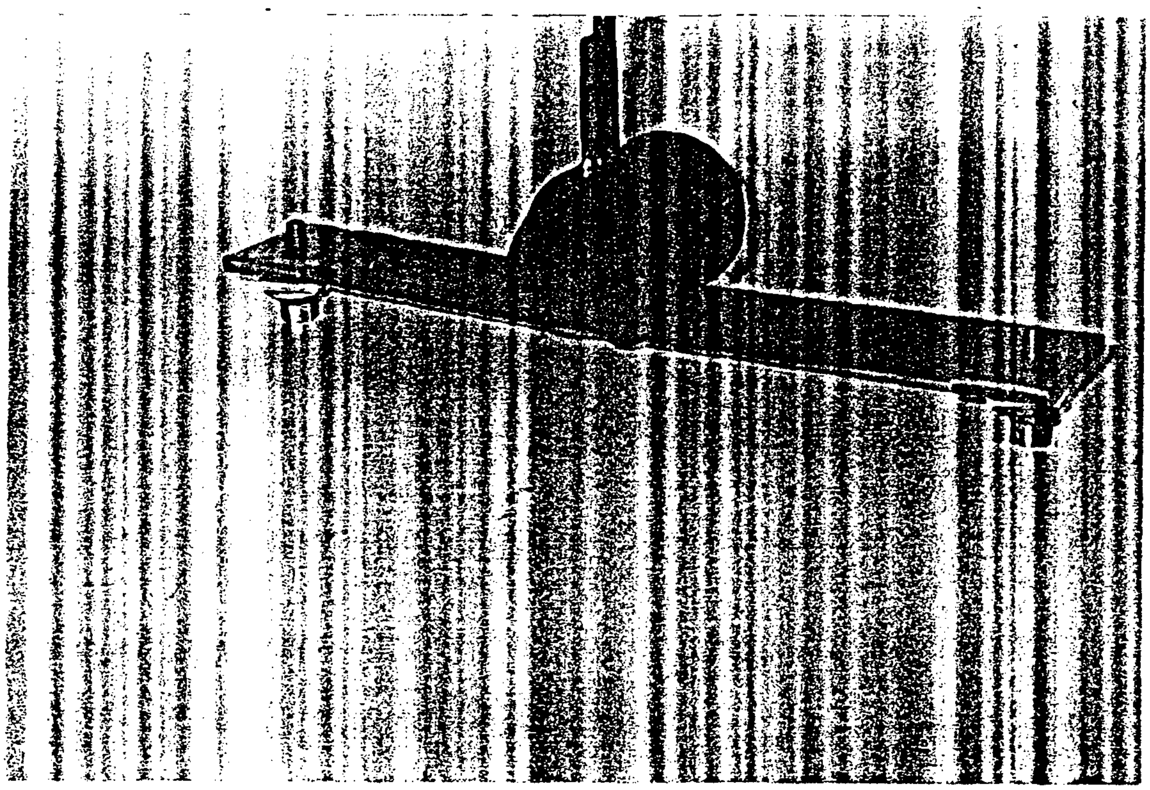

Fig.16 Photography of the simplified construction diffuser

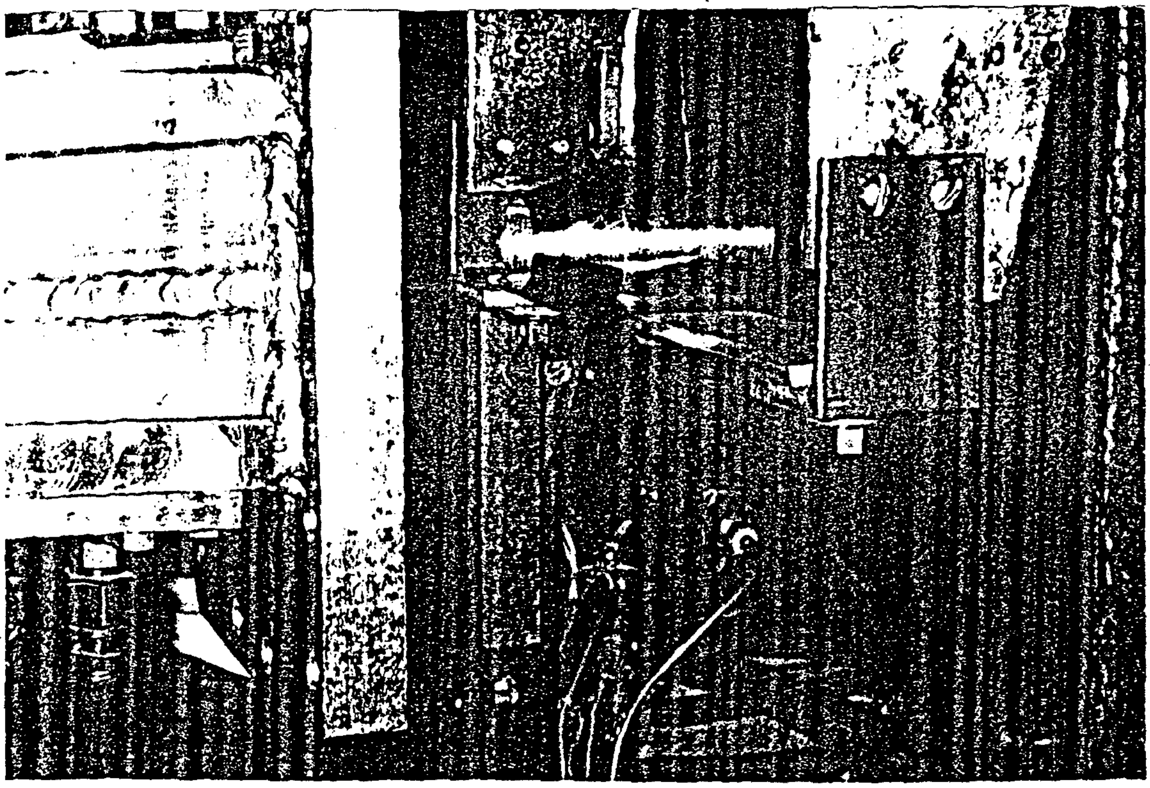

Fig.17 Photography of the simplified construction diffuser installation on the transversing equipment

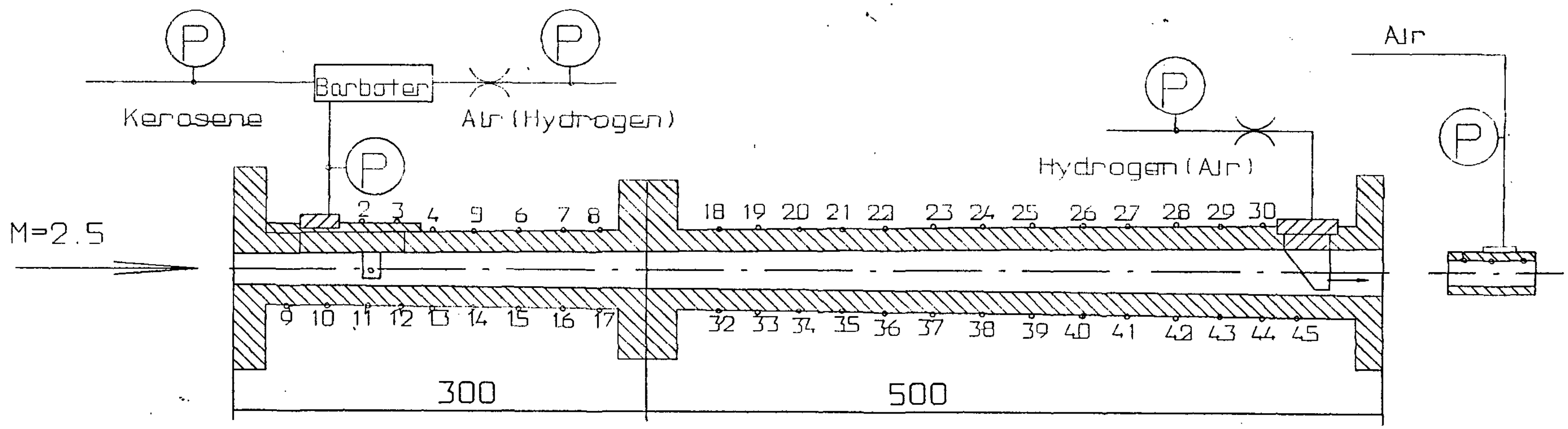

Fig. 18 Measurement schema in the channel and diffuser

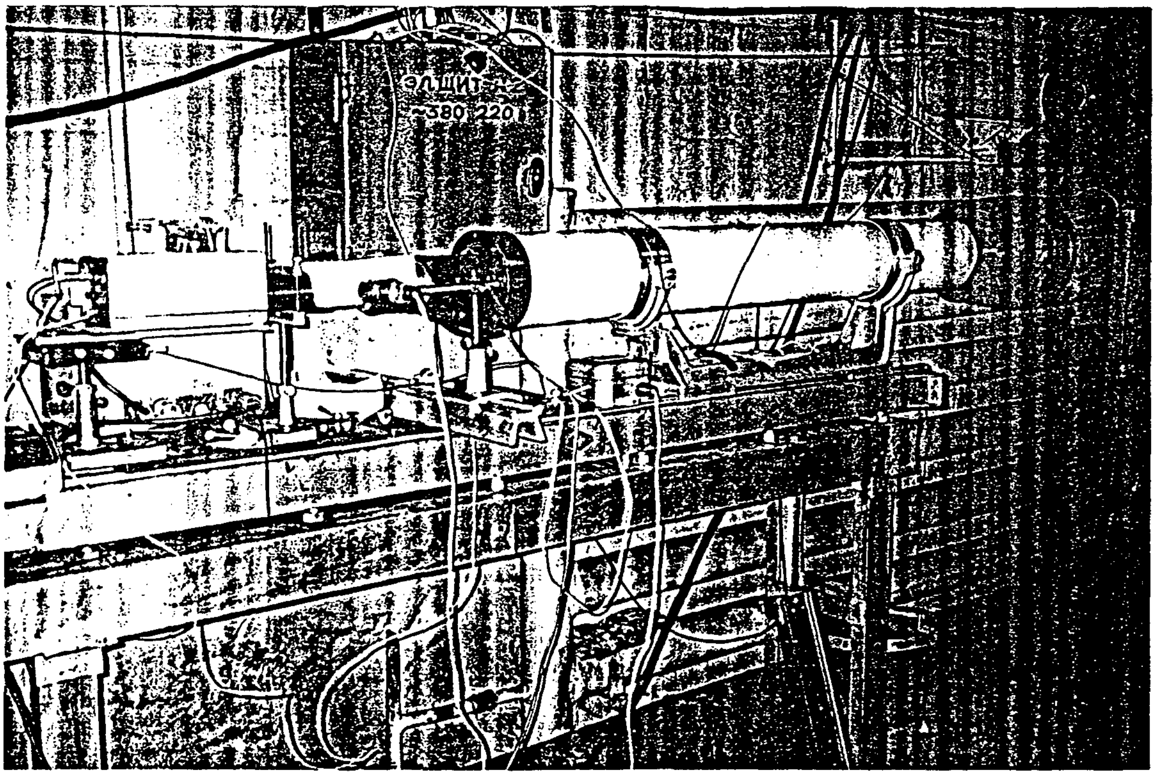

Fig.19 Photography of the schlieren device

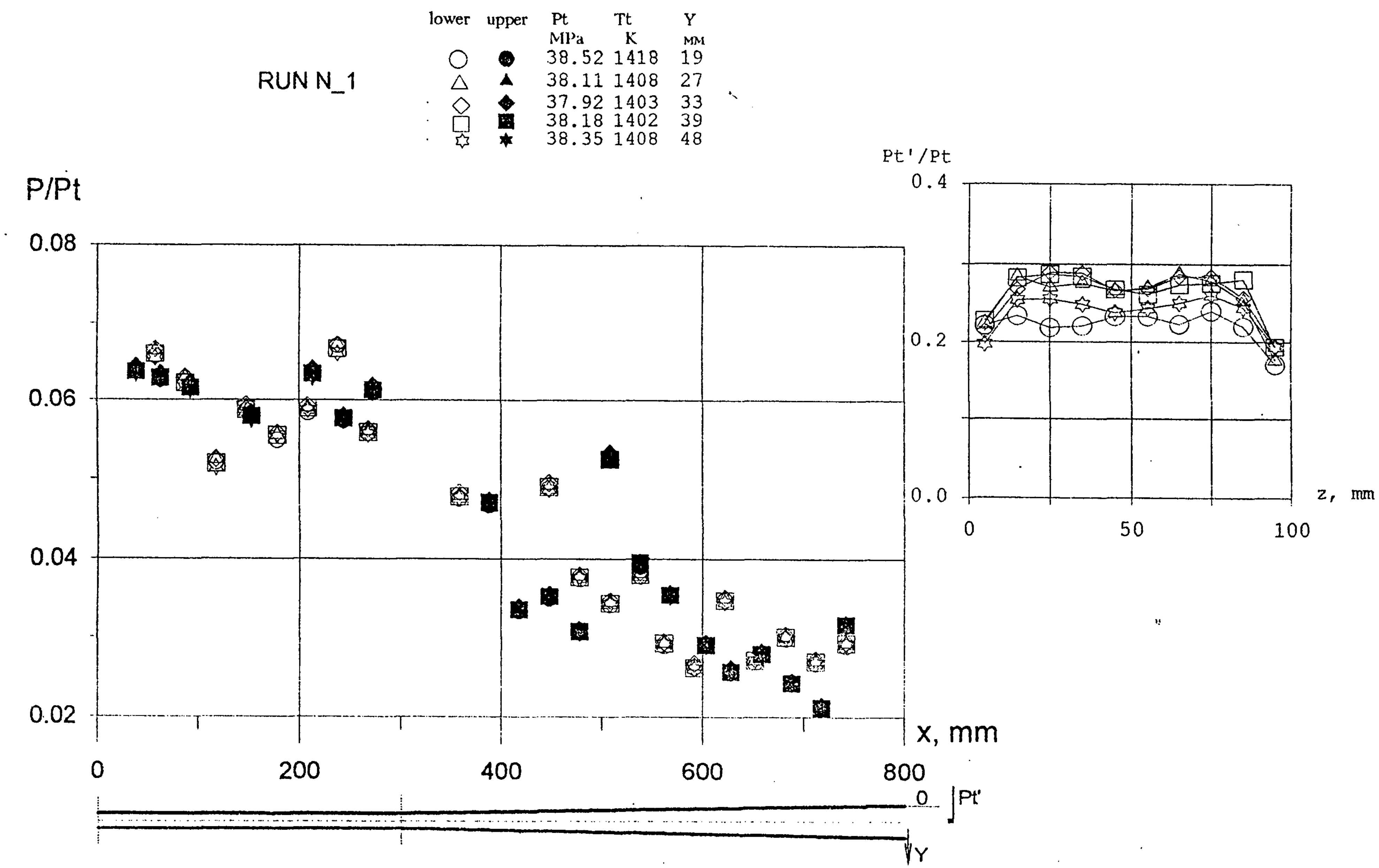

Fig.20 Axial static pressure distributions along channel walls and pitot pressure field in RUN No.1 at section x 18 mm from channel exit

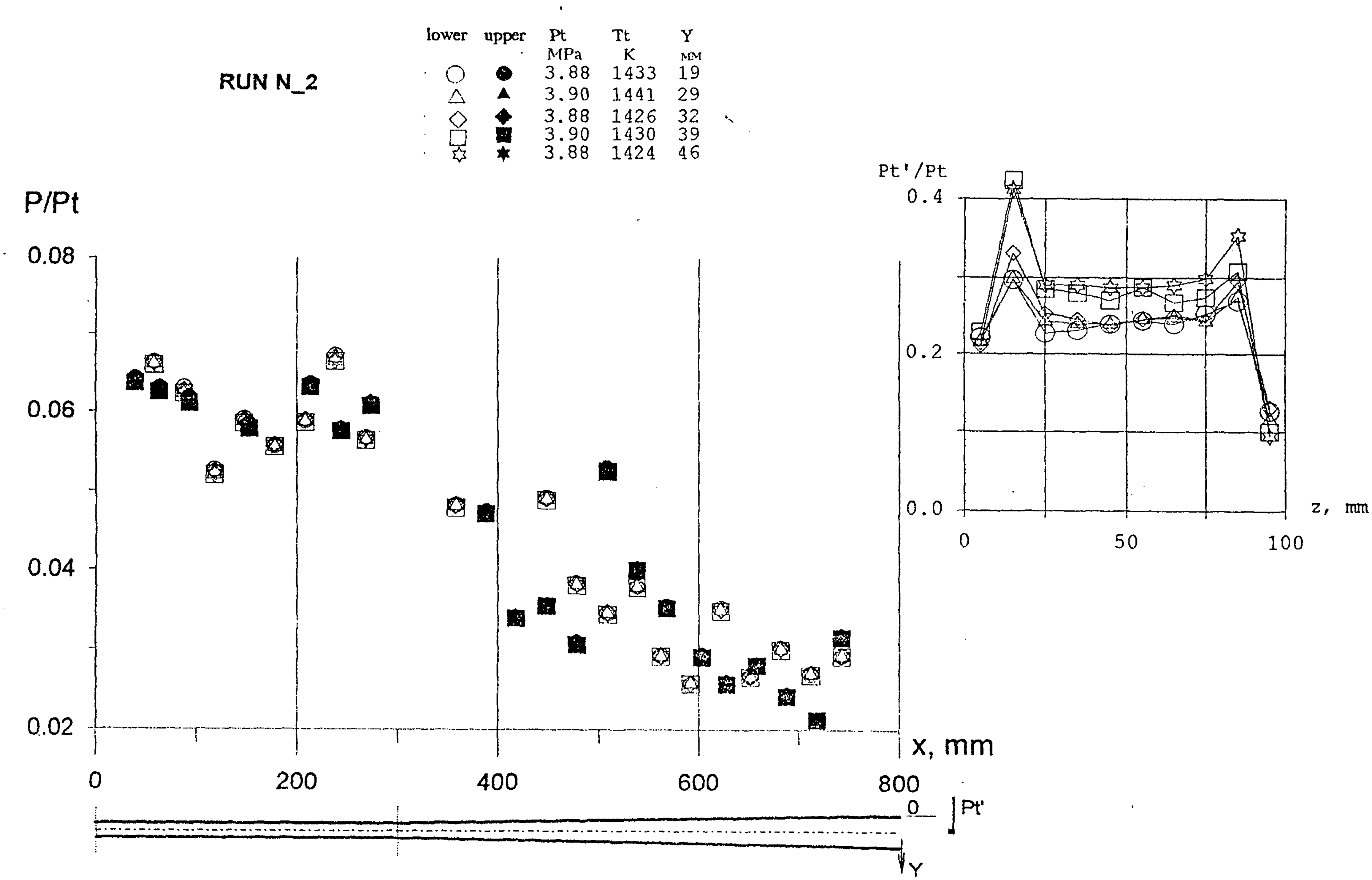

Fig.21 Axial static pressure distributions along channel walls and pitot pressure field in RUN No 2 at section x=50 mm from channel exit

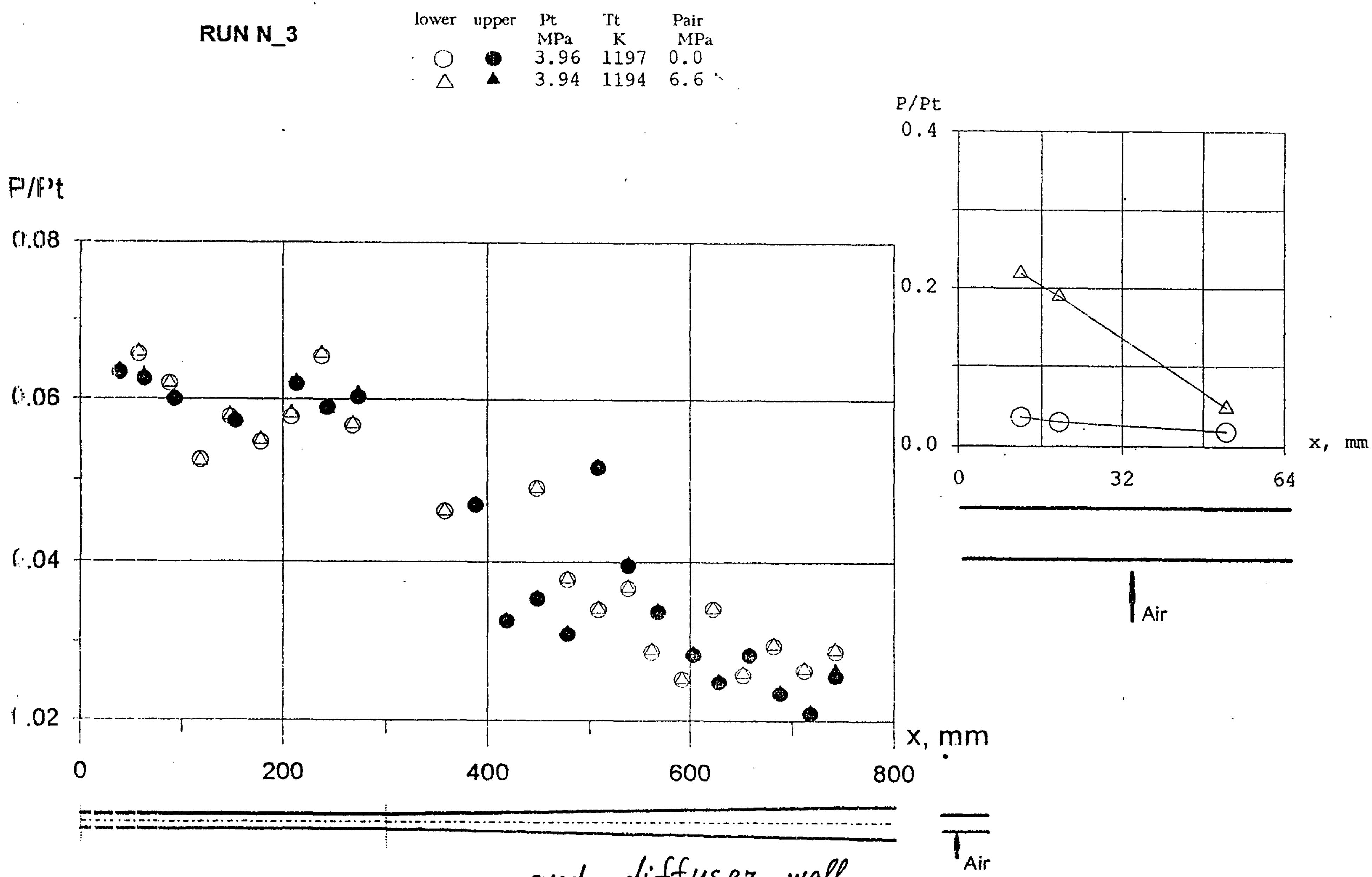

Fig.22 Axial static pressure distributions along channel walls and diffuser wall in RUN No 3

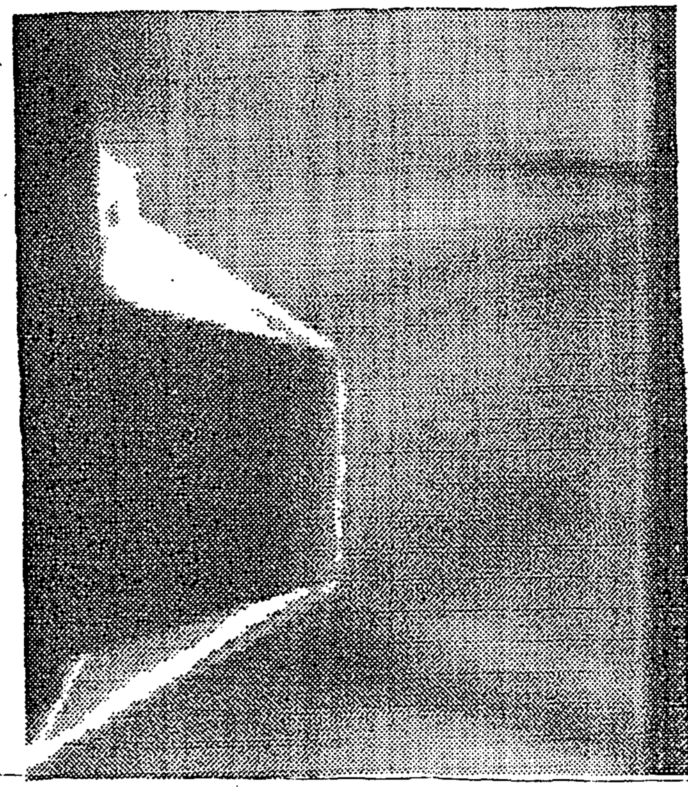

Fig.23a Schlieren picture of flowfield without diffuser throatling

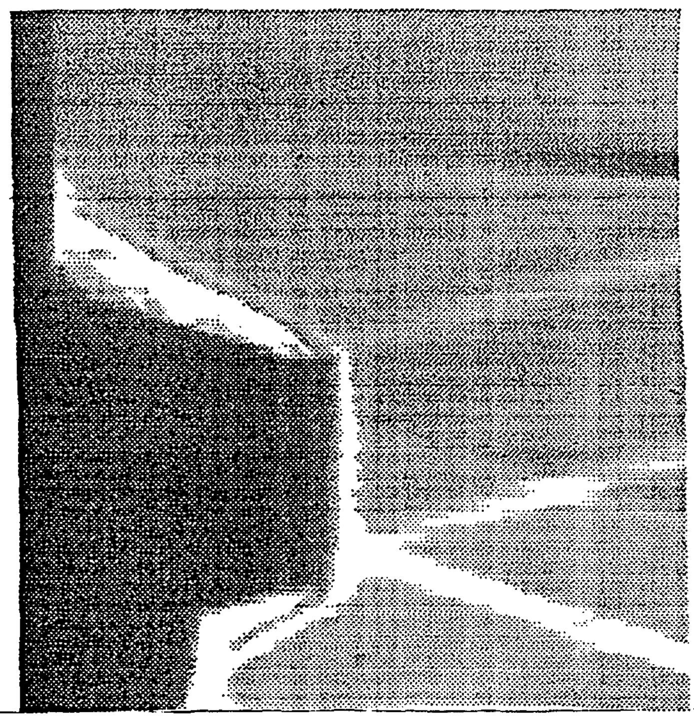

Fig.23b Schlieren picture of flowfield with diffuser throatling

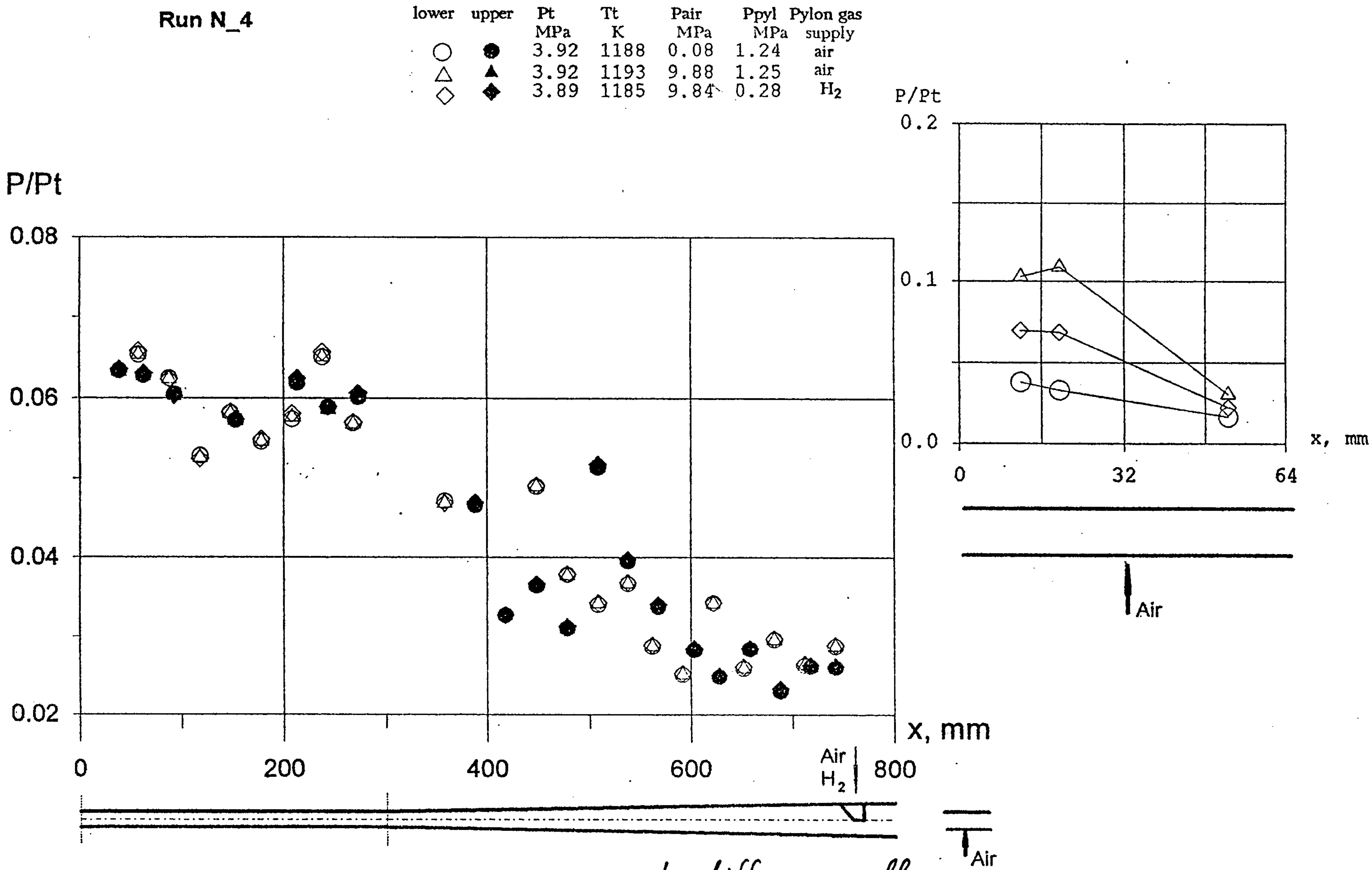

Fig.24 Axial static pressure distributions along channel walls and diffuser wall in RUN No 4

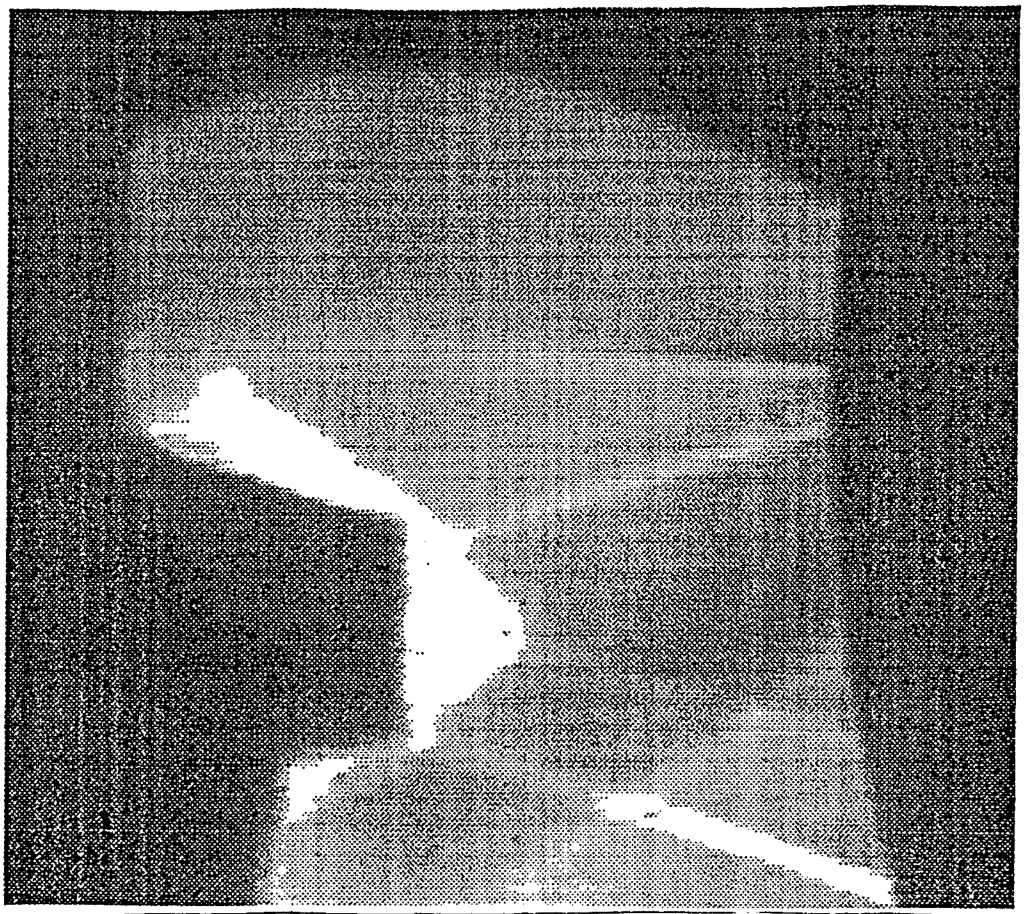

Fig.25a Schlieren picture of flowfield in RUN No 4
with air supply through-out vortex generator

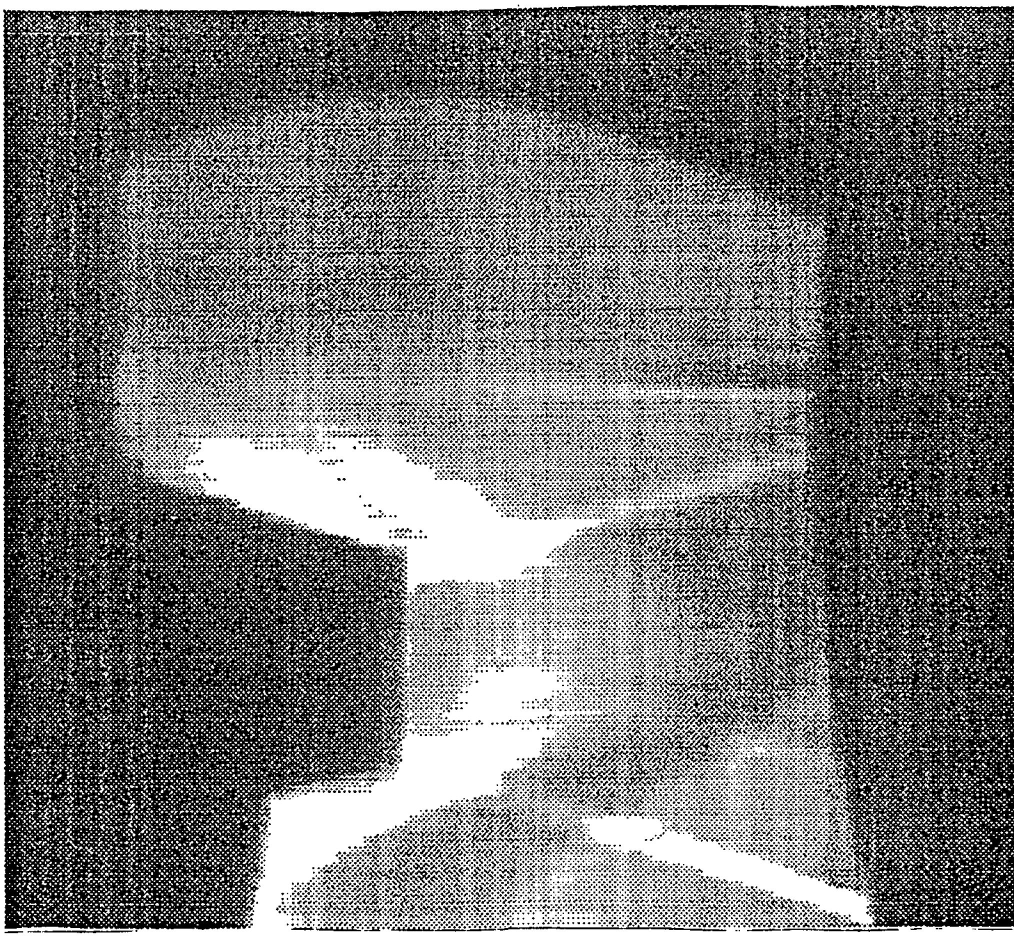

Fig.25b Schlieren picture of flowfield in RUN No 4
without air supply through-out vortex generator

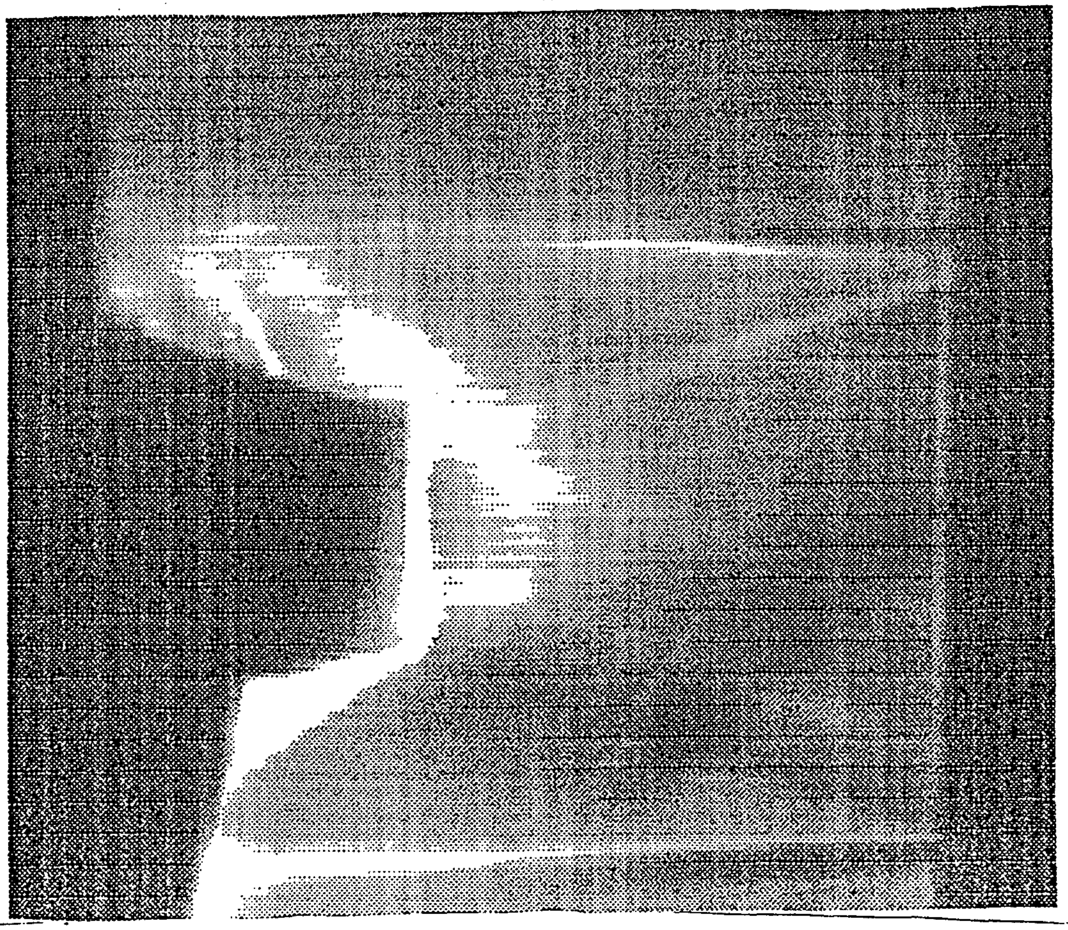

Fig.26a Schlieren picture of flowfield in RUN No 7 just before self - ignition

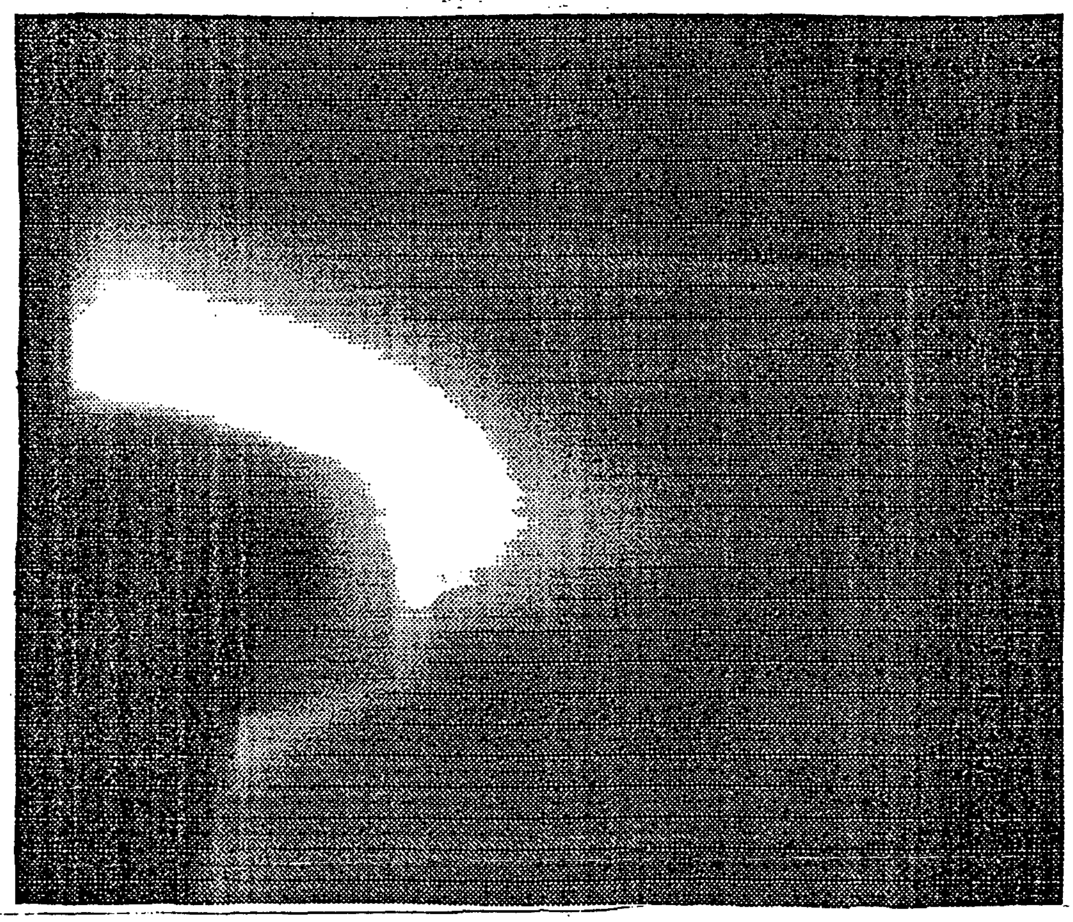

Fig.26b Schlieren picture of flowfield in RUN No 7 after self

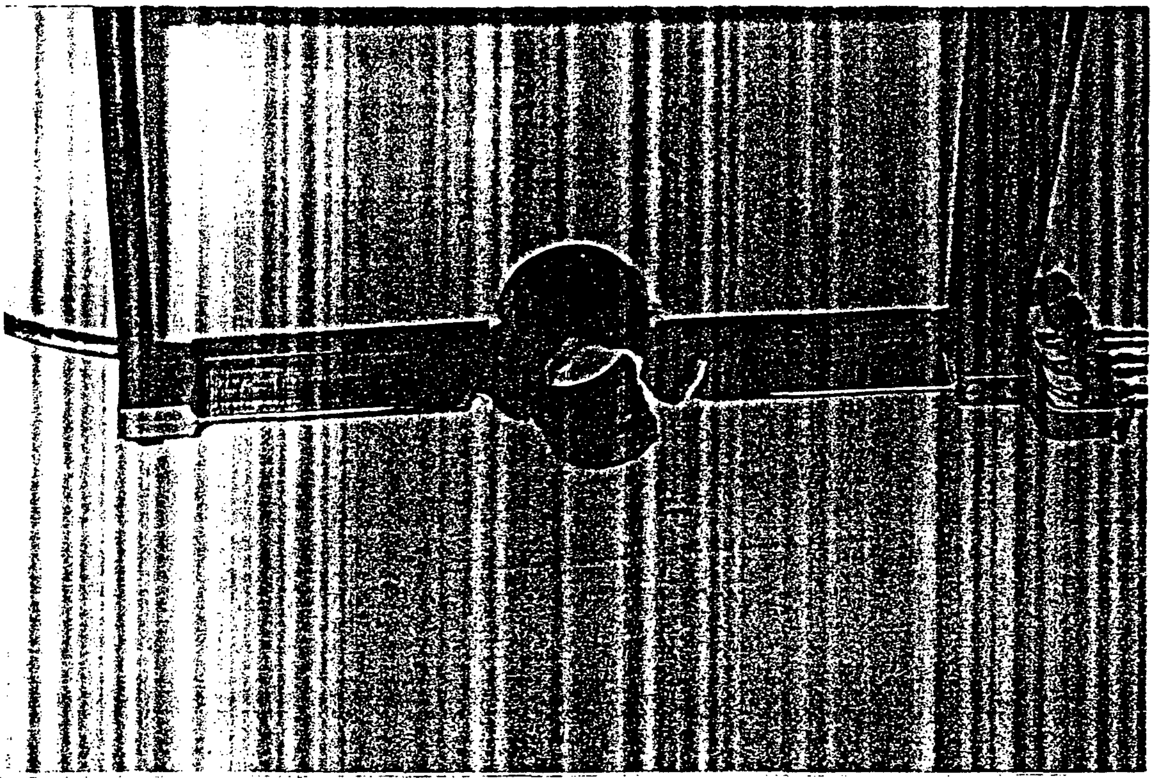

Fig.27 Photography of the damaged diffuser after experiment

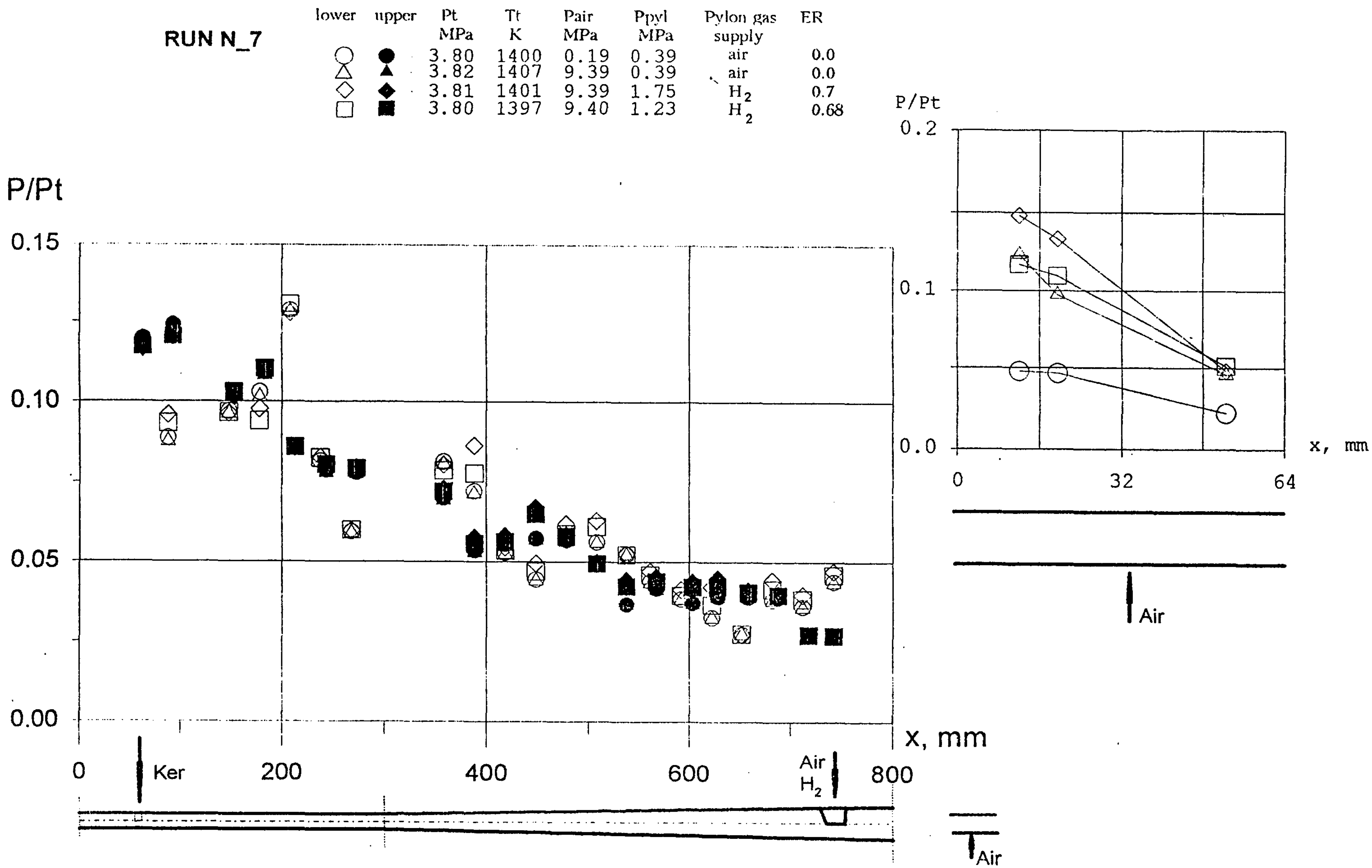

Fig.28 Axial static pressure distribution along channel walls and diffuser wall in RUN No 7

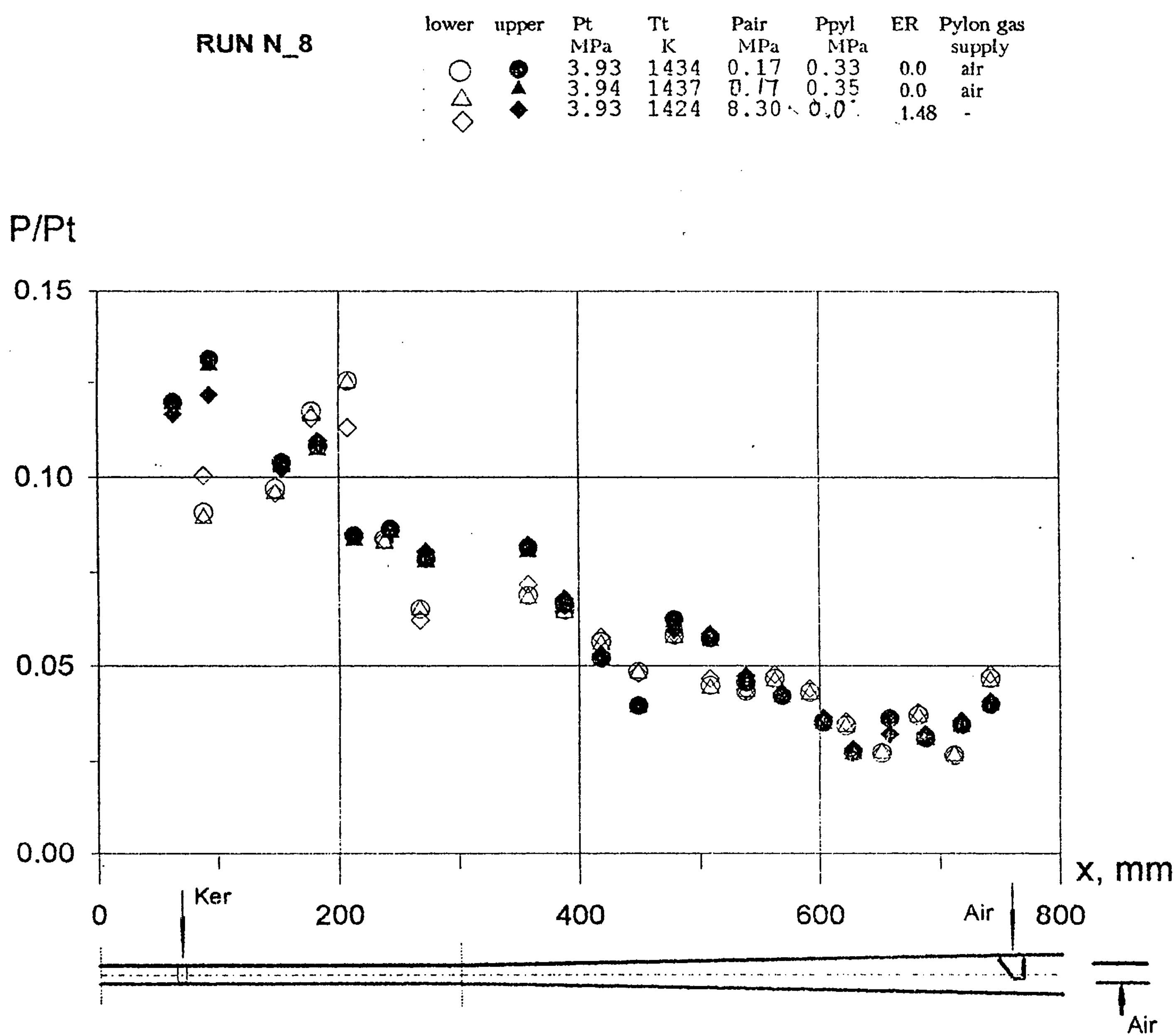

Fig.29 Axial static pressure distributions along channel walls in RUN No 8

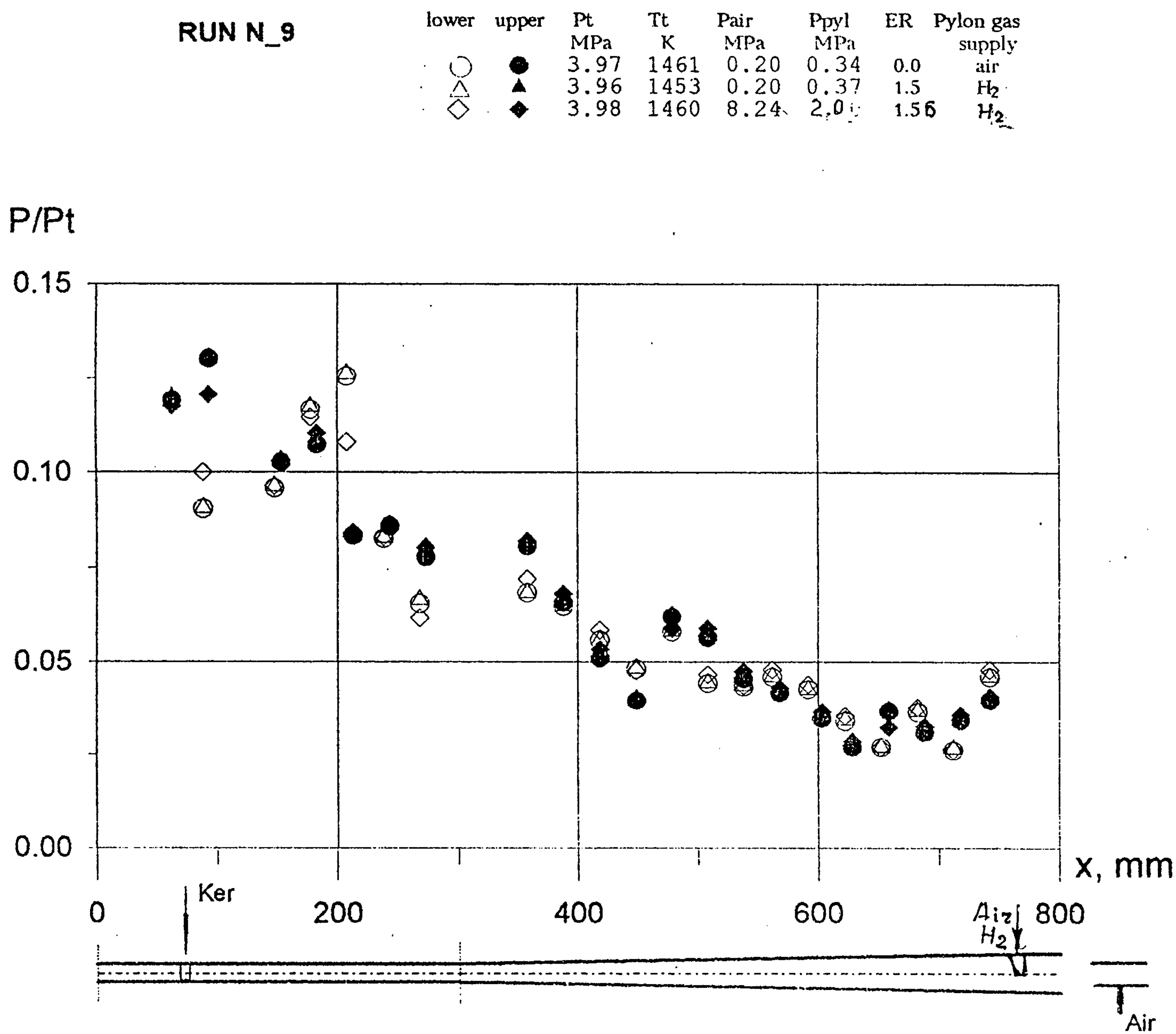

Fig.30 Axial static pressure distributions along channel walls in RUN No 9

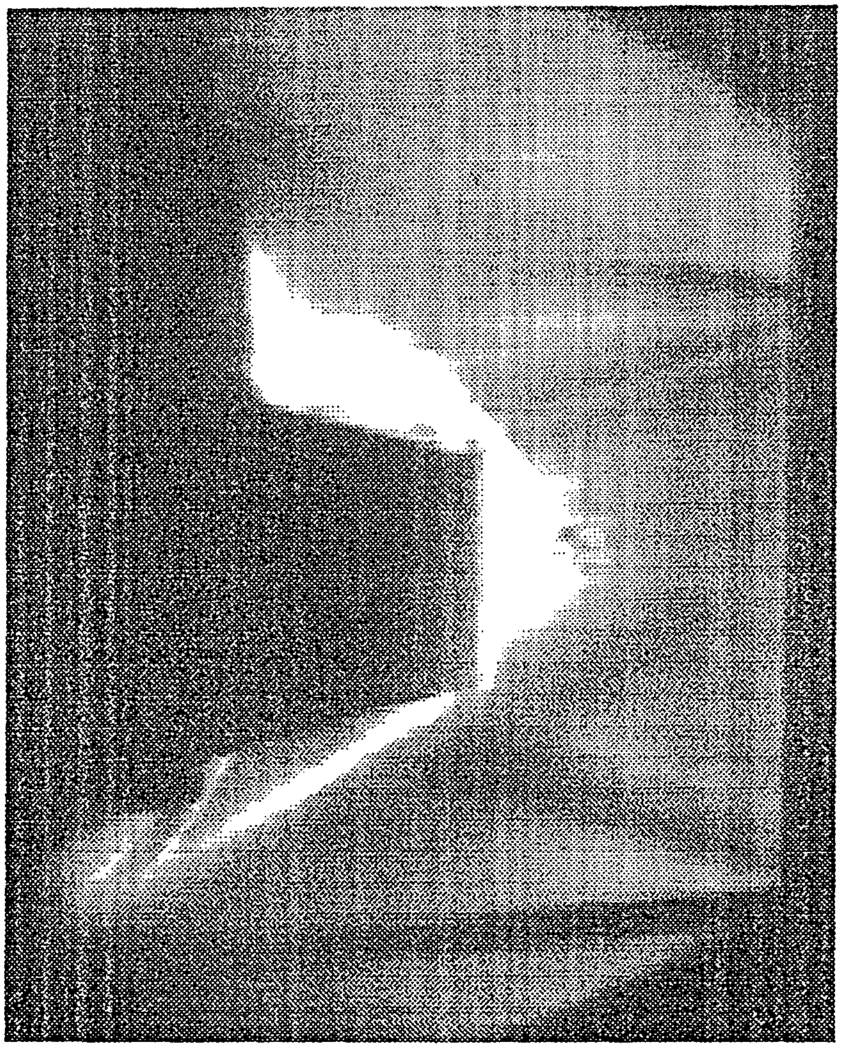

Fig.31 Schlieren picture of flowfield in RUN No 9

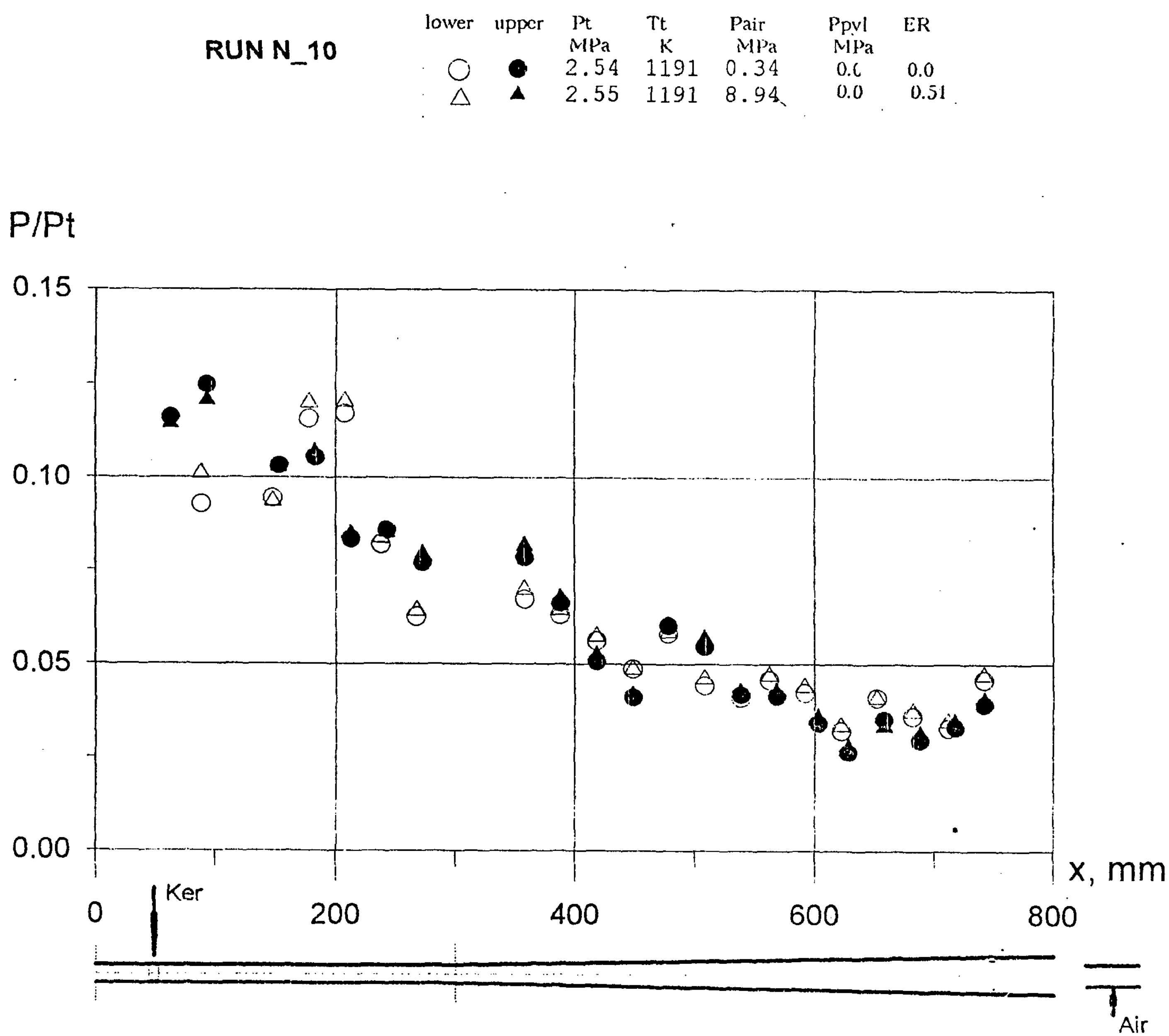

Fig.32 Axial static pressure distributions along channel walls in RUN No 10

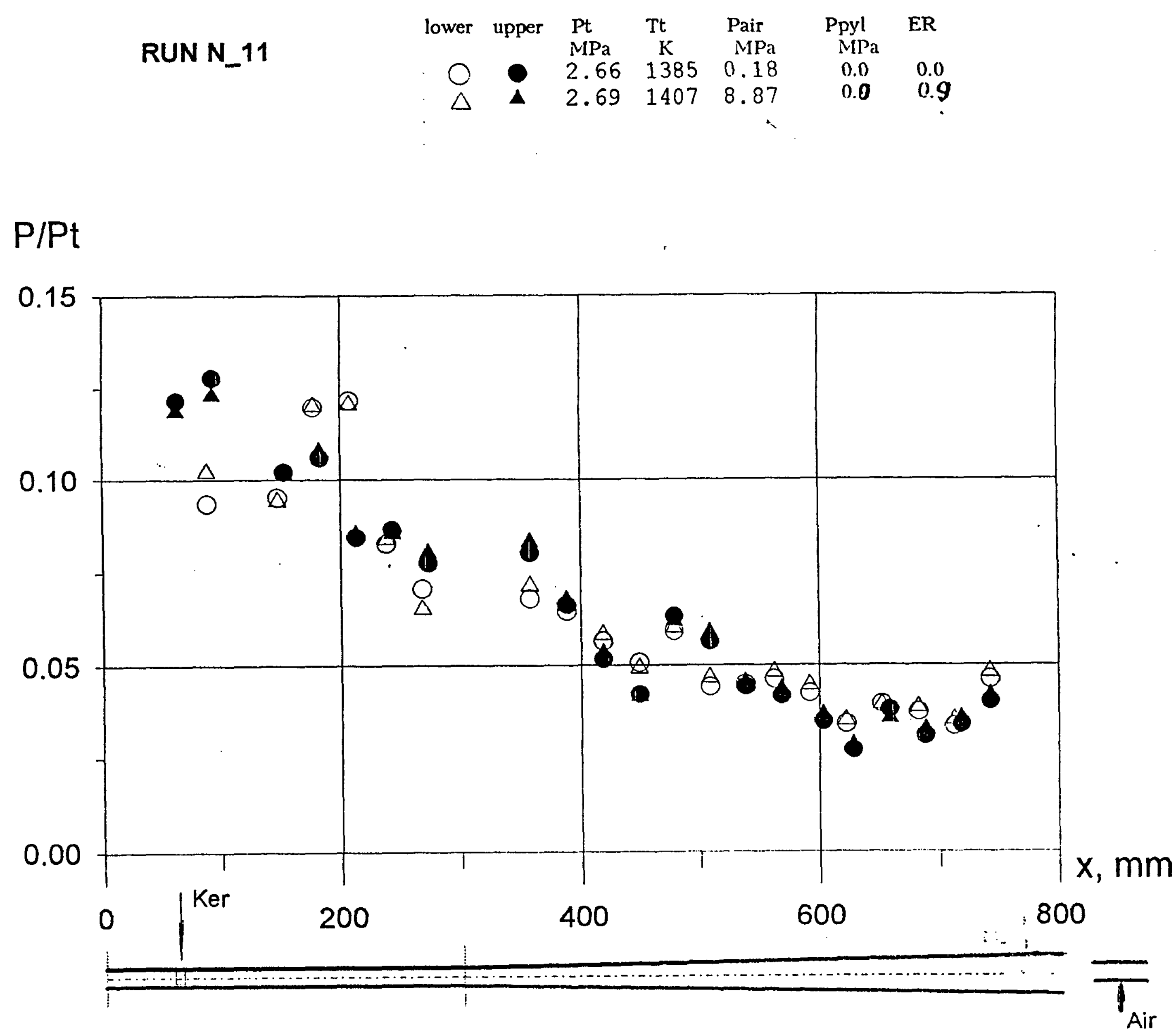

Fig.33 Axial static pressure distributions along channel walls in RUN No 11

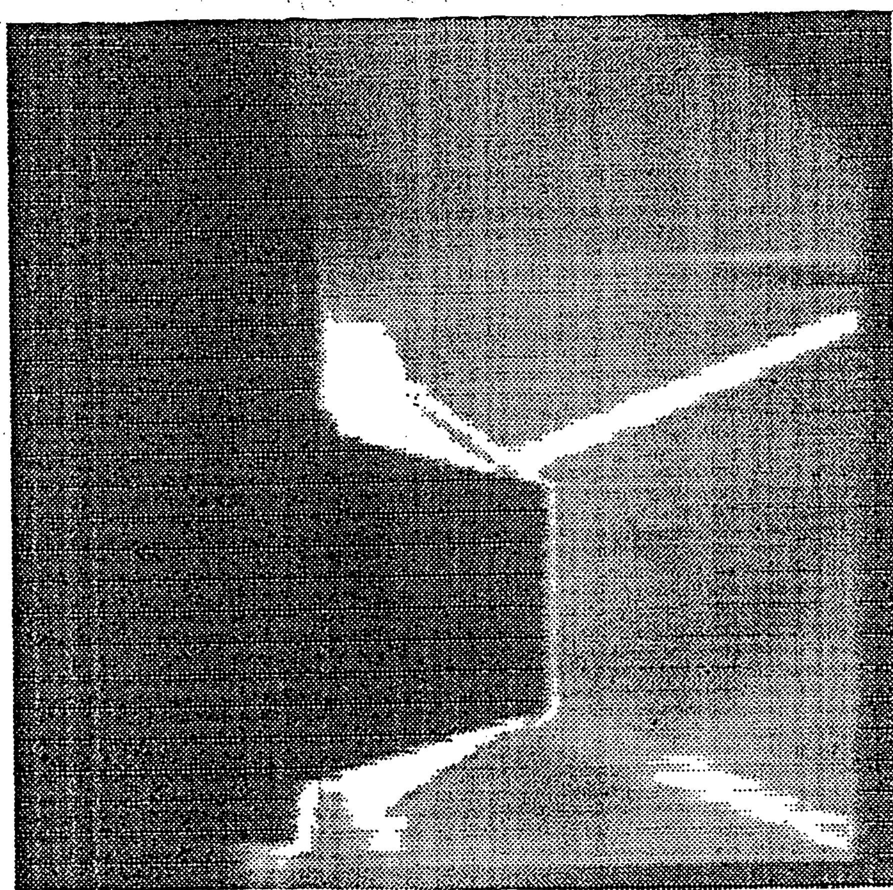

Fig.34a Schlieren picture of flowfield in RUN No 11 without diffuser throatling

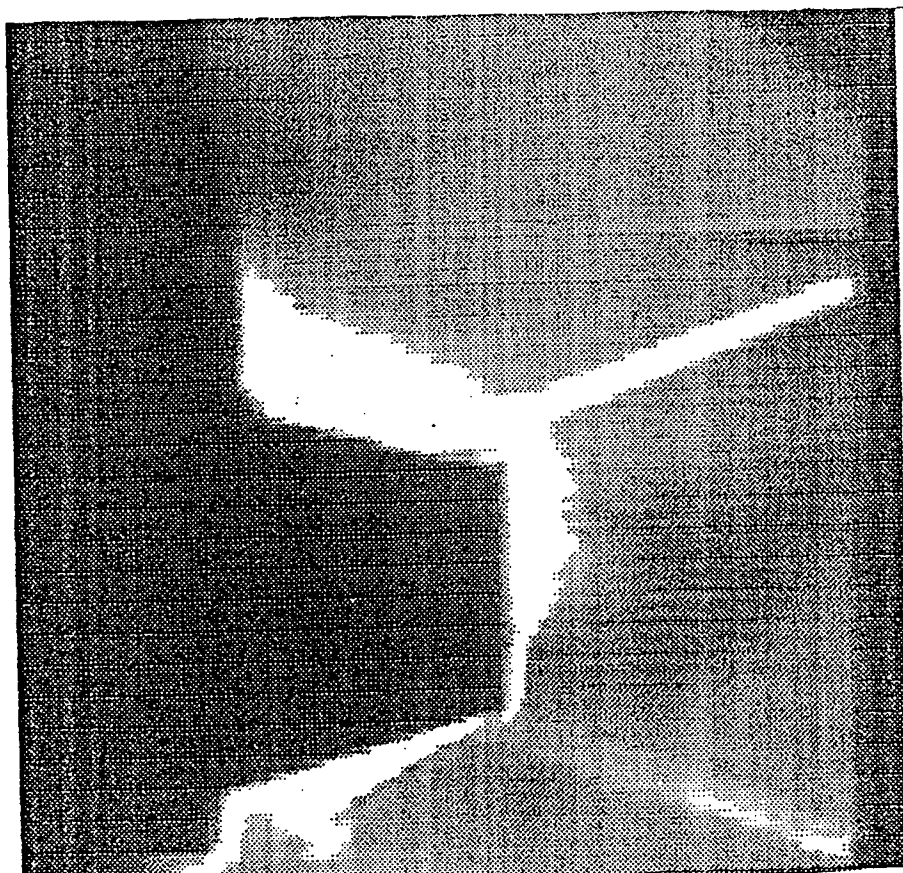

Fig.34b Schlieren picture of flowfield in RUN No 11 with diffuser throatling